

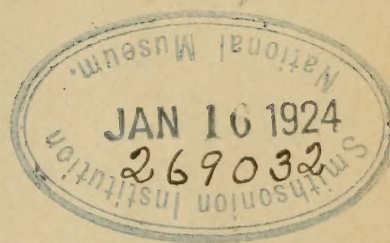
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CORRECTIONS AND INSERTIONS

Contributors to volume 34 have been invited to send corrections and insertions to be made in their papers, and the volume has been scanned with some care by the Editor. The following are such corrections and insertions as are deemed worthy of attention:

- Page 111, line 1 from top, *for* "Molengraaf" *read* Molengraaff
- " 113, line 17 from top, *for* "Christ Church, Canterbury College," *read* Canterbury College, Christ Church
- " 116, Summary, *for* "Original Fellows 25," *read* "Original Fellows 26"
- " 116, Summary, *for* "Membership 488," *read* "Membership 489"
- " 146, line 4 from top, *omit* word "iron"
- " 270, footnote 19, *for* "Manuscript submitted for publication," etc., *substitute* Bull. Am. Assoc. Pet. Geologists, vol. vii, 1923, pp. 1-13
- " 413, footnote 40, *insert* after "no." 78, May 25, 1923
- " 432, line 2 of figure title, *for* "contests" *read* contents
- " 435, bottom line, *for* "proportoin" *read* proportion
- " 506, explanation of figure 1, the finer vertical lines represent the "division-lines crossed by drainage"
- " 515, title of figure 8, line 3, *for* "Ledger dolomite" *read* Vintage dolomite

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OF THE GEOLOGICAL SOCIETY OF AMERICA, HELD AT
ANN ARBOR, MICHIGAN, THURSDAY-SATURDAY, DE-
CEMBER 28-30, 1922.

CHARLES P. BERKEY, *Secretary*

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SESSION OF THURSDAY MORNING, DECEMBER 28, 1922

The Thirty-fifth Annual Meeting of the Geological Society of America was called to order in the Natural Sciences Building of the University of Michigan, Ann Arbor, Michigan, at 10.22 a. m., by President Charles Schuchert. Brief remarks reminiscent of the influence of the University of Michigan in American geology were made by President Schuchert,

who called attention to the fact that this was early a center of geological activity under the influence of Alexander Winchell, the real father of the Geological Society of America and one of its earliest Presidents, as well as under his successor, Israel C. Russell, who also became a President of this Society. He pointed out that Ann Arbor, both because of its former great influence and also because of its continued prominence to the present day as an active center of geological teaching and investigation, is a very appropriate place for this annual meeting of the Geological Society and its affiliated societies, covering the geologic, mineralogic, paleontologic, geographic, and physiographic fields of investigation.

REPORT OF THE COUNCIL

The report of the Council was presented by Secretary Hovey, as follows:

To the Geological Society of America, in thirty-fifth annual meeting assembled:

The regular annual meeting of the Council was held at Amherst, Massachusetts, in connection with the meeting of the Society, December 28-30, 1921. A special meeting was held in New York on October 15, 1922.

The details of administration for the thirty-fourth year of the existence of the Society are given in the following reports of the officers:

SECRETARY'S REPORT

To the Council of the Geological Society of America:

The Secretary's annual report for the year ending November 30, 1922, is as follows:

Meetings.—The proceedings of the annual general meeting of the Society, held at Amherst, Massachusetts, December 28-30, 1921, have been recorded in volume 33, pages 1-186, of the Bulletin. Those of the Cordilleran Section, pages 187-190; of the Paleontological Society, pages 191-222; of the Society of Economic Geologists, pages 223-226; of the Mineralogical Society of America, pages 227-230, of the same volume.

Membership.—During the last year the Society has lost five Fellows by death—John C. Branner, R. D. Salisbury, James E. Todd, Levi Holbrook, and G. H. Cox. The names of the twenty-one Fellows elected at the Amherst meeting who qualified have been added to the printed list. Six Fellows have resigned or been dropped for non-payment of

dues. The present enrollment of the Society is 463. Sixteen candidates for Fellowship are before the Society for election and several applications are under consideration by the Council.

Distribution of the Bulletin.—During the past year there have been sent out to subscribers 158 copies of volume 33 of the Bulletin. Five volumes have been distributed gratis, as follows: Library of Congress, American Museum of Natural History, the Government Geological Surveys of the United States, Canada, and Mexico. Fifty-eight copies have been sent to our foreign exchange list. The receipts from subscriptions to and sales of the Bulletin and separate brochures therefrom appear in the following table:

PROCEEDINGS OF THE ANN ARBOR MEETING

Bulletin Sales, December 1, 1921–November 30, 1922

	Complete volumes.			Brochures and parts.			Grand total.
	Fellows.	Public.	Total.	Fellows.	Public.	Total.	
Volume 1...							
Volume 2...					\$1.74	\$1.74	\$1.74
Volume 3...				\$1.25	.45	1.70	1.70
Volume 4...					.20	.20	.20
Volume 5...				.30	1.05	1.35	1.35
Volume 6...				.15	1.65	1.80	1.80
Volume 7...		\$7.50	\$7.50				7.50
Volume 8...					1.88	1.88	1.88
Volume 9...							
Volume 10...							
Volume 11...					1.30	1.30	1.30
Volume 12...							
Volume 13...							
Volume 14...							
Volume 15...					2.30	2.30	2.30
Volume 16...					1.02	1.02	1.02
Volume 17...		7.50	7.50				7.50
Volume 18...		7.50	7.50	1.45		1.45	8.95
Volume 19...		7.50	7.50		1.30	1.30	8.80
Volume 20...				3.90	.35	3.35	3.35
Volume 21...							
Volume 22...		7.50	7.50		.90	.90	8.40
Volume 23...		7.50	7.50	1.00	.70	1.70	9.20
Volume 24...					1.25	1.25	1.25
Volume 25...				1.60		1.60	1.60
Volume 26...				.95	.49	1.44	1.44
Volume 27...				2.70	1.00	3.70	3.70
Volume 28...				4.50	11.10	15.60	15.60
Volume 29...		7.50	7.50	.95	7.48	8.43	15.93
Volume 30...		32.50	32.50	4.50	107.80	112.30	144.80
Volume 31...		46.50	46.50	4.70	8.16	12.86	59.36
Volume 32...	\$7.50	72.00	79.50	2.20	32.65	34.85	114.35
Volume 33...		1,236.50	1,236.50	9.00	12.09	21.09	1,257.59
Volume 34...		270.00	270.00				270.00
Overpayment							2.91
Total....	7.50	1,710.00	1,717.50	38.25	196.86	235.11	1,955.52
Index 21-30..		48.00	48.00				48.00
Total....	\$7.50	\$1,758.00	\$1,765.50	\$38.25	\$196.86	\$235.11	\$2,003.52

Receipts for the fiscal year..... \$2,003.52

Previously reported..... 29,553.05

Total receipts to date..... \$31,556.57

Respectfully submitted,

EDMUND OTIS HOVEY,
Secretary.

TREASURER'S REPORT

To the Council of the Geological Society of America:

The Treasurer herewith submits his annual report for the year ending November 30, 1922.

The membership of the Society at the present time is 463, of whom 372 pay annual dues. Twenty-two new members were elected at the last annual meeting, 21 of whom qualified. One elected in 1920 also qualified, making a total of 22 new members. Four members commuted for life, making the total Life Membership 91. There have been 5 deaths during the year. When the books closed for the year 26 members were delinquent in the payment of dues—2 for 4 years, 3 for 3 years, 4 for 2 years—and are therefore liable to be dropped from the roll, and 17 for 1 year.

RECEIPTS

Cash on hand December 1, 1921.....	\$1,684.96	
Fellowship fees: 1918 (1).....	\$10.00	
1919 (1).....	10.00	
1920 (4).....	40.00	
1921 (23).....	230.00	
1922 (351).....	3,510.00	
		3,800.00
Initiation fees (21 for 1921 + 1 for 1920).....	220.00	
Life commutations (4).....	587.00*	
Interest on investments.....	1,420.00	
Interest on deposits in Baltimore Trust Company.....	124.85	
Amounts added to checks.....	2.29	
Refund on bond premium.....	7.50	
Redemption of New York Central bond.....	1,050.00	
Case Library on account.....	300.00	
Received from Secretary:		
Sales of publications.....	\$2,003.52	
Author's separates.....	334.65	
Author's corrections refunded.....	26.21	
Postage refunded.....	23.83	
Engraver's charge refunded.....	5.00	
Exchange on checks refunded.....	1.89	
Binding	3.25	
Group portraits.....	12.00	
Geological Magazine.....	222.25	
Printing	2.50	
Alterations	4.40	
		2,639.50
		<u>\$11,836.10</u>

* \$7.00 overpayment subsequently returned.

DISBURSEMENTS

Secretary's office :		
Administration	\$415.79	
Bulletin	507.58	
Portrait	5.00	
Geological Magazine.....	247.53	
Salary	1,000.00	
		\$2,175.90
Treasurer's office :		
Expenses	\$66.50	
Clerk	150.00	
		216.50
Publication of Bulletin :		
Printing	\$2,497.07	
Engraving	697.28	
Editor's salary.....	250.00	
		3,444.35
Mineralogical Society of America.....		93.00
Refund on account of overpayment on Life Membership.		7.00
Investments :		
1 Braden Copper Mines bond.....	\$1,010.83	
1 Commonwealth Edison Company bond..	1,002.22	
		2,013.05
Balance in Baltimore Trust Company.....		3,886.30
		\$11,836.10
Respectfully submitted,		EDWARD B. MATHEWS,
		<i>Treasurer.</i>

EDITOR'S REPORT

To the Council of the Geological Society of America:

The following tables cover statistical data for the thirty-three volumes thus far issued :

ANALYSIS OF COSTS OF PUBLICATION

Cost.	Average— Vols. 1-30.	Vol. 31.	Vol. 32.	Vol. 33.
	pp. 737. pls. 31.	pp. 468. pls. 14.	pp. 506. pls. 12.	pp. 883. pls. 5.
Letter press.....	\$1,776.16	\$1,541.45	\$1,883.18	\$3,006.32
Illustrations.....	433.34	131.94	272.44	616.01
Paper.....	428.12	266.64	792.00	686.81
Total	\$2,566.03	\$1,940.03	\$2,947.62	\$4,309.14
Average per page	\$3.51	\$4.15	\$5.83	\$4.85

CLASSIFICATION OF SUBJECT-MATTER

Volume.	Areal geology.	Physical geology.	Glacial geology.	Physiographic geology.	Petrographic geology.	Stratigraphic geology.	Paleontologic geology.	Economic geol-ogy.	Official matter.	Memorials.	Unclassified.	Total.
	Number of Pages.											
1	116	137	92	18	83	44	47	---	60	4	4	593+xii
2	56	110	60	111	52	168	47	9	55	1	7	662+xiv
3	56	41	44	41	32	153	104	---	61	15	1	541+xii
4	25	134	38	74	52	52	14	---	47	32	2	458+xii
5	138	135	70	54	28	51	107	---	71	14	9	665+xii
6	50	111	75	39	71	99	1	---	63	25	4	538+x
7	38	77	105	53	40	21	123	4	66	28	13	558+x
8	34	50	98	5	43	67	58	14	79	8	---	46+x
9	2	102	138	---	44	28	64	16	64	12	---	60+x
10	35	33	96	37	59	62	68	28	84	27	17	534+xiii
11	65	110	21	10	54	31	188	7	71	60	46	651+xii
12	199	39	55	53	24	98	5	5	70	2	---	538+xi
13	125	17	13	24	28	116	42	4	165	32	29	583+xii
14	48	47	48	59	183	118	22	1	80	14	1	609+xi
15	26	124	3	94	36	267	---	---	77	17	3	636+x
16	64	111	78	30	102	141	19	---	67	22	15	636+xiii
17	49	161	41	84	47	294	27	---	71	9	2	785+xiv
18	16	164	141	5	29	246	5	---	68	40	3	717+xii
19	106	108	29	66	30	155	32	---	56	15	20	617+x
20	43	54	35	29	37	45	303	8	60	3	132	749+xiv
21	72	234	75	48	85	70	106	1	111	11	10	823+xvi
22	23	54	28	28	23	403	74	---	63	49	1	747+xii
23	75	52	126	108	19	145	134	---	66	32	1	758+xvi
24	18	57	96	57	49	160	106	23	133	53	3	737+xviii
25	34	211	54	32	156	9	175	---	108	9	22	802+xviii
26	---	72	23	11	56	90	148	---	54	44	6	504+xxi
27	1	59	125	31	146	20	271	2	73	24	5	739+xviii
28	25	273	70	69	78	200	55	39	94	110	14	1005+xxii
29	3	107	62	15	127	169	64	---	73	57	21	679+xix
30	160	3	41	9	5	36	205	16	73	59	50	644+xiii
31	1	80	19	4	13	45	22	21	69	97	79	450+xviii
32	73	47	7	27	63	51	77	17	105	2	37	488+xviii
33	39	166	160	47	97	107	101	3	91	41	31	862+xxi

Respectfully submitted,

JOSEPH STANLEY-BROWN, *Editor.*

The foregoing report is respectfully submitted.

THE COUNCIL.

December 28, 1922.

ELECTION OF AUDITING COMMITTEE

The printed report of the Council was distributed to the members in attendance and was available for additional circulation. Since the report of the Council contained the Treasurer's report, it was laid on the table

pending report of an auditing committee named from the floor, consisting of H. B. Kummel, Harry Fielding Reid, and R. T. Chamberlin.

ELECTION OF OFFICERS, MEMBERS OF STANDING COMMITTEES, AND
FELLOWS

The Secretary then declared the vote for officers, members of standing committees, and Fellows for 1923, resulting from the canvas made by mail, as follows:

President:

DAVID WHITE, Washington, D. C.

First Vice-President:

WILLIAM H. HOBBS, Ann Arbor, Michigan

Second Vice-President:

WILLIAM H. EMMONS, Minneapolis, Minnesota

Third Vice-President:

T. WAYLAND VAUGHAN, Washington, D. C.

Vice-President to represent the Mineralogical Society of America:

EDGAR T. WHERRY, Washington, D. C.

Secretary:

CHARLES P. BERKEY, New York City

Treasurer:

EDWARD B. MATHEWS, Baltimore, Maryland

Editor:

JOSEPH STANLEY-BROWN, New York City

Councilors (1923-1925):

EDMUND OTIS HOVEY, New York City

ALFRED H. BROOKS, Washington, D. C.

*Representatives on the National Research Council (July 1, 1923, to
June 30, 1926):*

ADOLPH KNOFF, New Haven, Connecticut

FREDERICK B. LOOMIS, Amherst, Massachusetts

*Members of the Standing Committee on Teaching of Geology
(1923-1925):*

ELIOT BLACKWELDER, Stanford University, California
WARREN J. MEAD, Madison, Wisconsin

FELLOWS

LEASON H. ADAMS, B. S., Geophysical Laboratory, Washington, D. C.
EUGENE T. ALLEN, Ph. D., Geophysical Laboratory, Washington, D. C.
PAUL BILLINGSLEY, A. B., Anaconda Copper Mining Company, Portage, Washington.
JOHN STAFFORD BROWN, B. S., Associate Geologist, U. S. Geological Survey, Washington, D. C.
KIRK BRYAN, Ph. D., Geologist, U. S. Geological Survey, Washington, D. C.
VICTOR DOLMAGE, Ph. D., Canadian Geological Survey, Ottawa, Canada.
JAMES WILLIAMS GIDLEY, Ph. D., U. S. National Museum, Washington, D. C.
ANNA I. JONAS, Ph. D., Bridgeton, New Jersey.
BERTRAM REID MACKAY, Ph. D., Geological Survey of Canada, Ottawa, Canada.
ALEXANDER WATTS MCCOY, M. A., Bartlesville, Oklahoma.
DONALD HAMILTON McLAUGHLIN, Ph. D., Berkeley, California.
MAURICE GOLDSMITH MEHL, Ph. D., University of Missouri, Columbia, Missouri.
CHARLES CRAIG MOOK, Ph. D., Metuchen, New Jersey, Research Assistant, American Museum of Natural History.
STANLEY SMITH, D. Sc., Assistant Professor in Geology, Queens University, Kingston, Ontario.
WILLIAM LAWRENCE UGLOW, Ph. D., University of British Columbia, Vancouver, Canada.
HARRY OSCAR WOOD, A. M., Mount Wilson Observatory, Pasadena, California.
E. G. WOODRUFF, M. A., Geologist, New England Oil and Pipe Company, Tulsa, Oklahoma.

VOTE ON PROPOSED AMENDMENT TO THE CONSTITUTION

The proposed amendment was as follows:

Resolved, That section 4 of Article V of the Constitution be amended by deleting the words "the Council," in the first line of the section, and substituting therefor the words "trial ballot by the Fellows."

The President announced that the vote called for by mail on the adoption of the proposed constitutional amendment resulted in 87 in favor of the proposed amendment and 99 against it (required to adopt, 347), and that therefore the amendment was defeated. He called attention to the fact that with this result it was unnecessary to present the corresponding amendment to the By-Laws, which hinged directly on the adoption of the proposed amendment to the Constitution. No further action was taken by the Society.

INTRODUCTION OF CORRESPONDENT EMMANUEL DE MARGERIE

President Schuchert at this point introduced Prof. Emmanuel de Margerie, Director of the Geological Survey of Alsace and Correspondent of the Geological Society of America, calling attention to the fact that this is the first time in the history of the Society that a Correspondent has attended one of its meetings. Professor de Margerie responded briefly, speaking in a very appreciative manner of the work and influence of the Geological Society.

REPORT OF THE REPRESENTATIVE TO THE INTERNATIONAL GEOLOGICAL CONGRESS

Edward B. Mathews gave a brief oral report of his service as representative to the International Geological Congress.

REPORT OF COMMITTEE ON TEACHING GEOLOGY

H. F. Cleland, chairman of the Committee on the Teaching of Geology, submitted a report by letter, which was read by the Secretary, as follows:

During the past year the committee has endeavored to carry out some of its recommendations of last year. In that report it was recommended that geological models of ten of the principal physiographic provinces be constructed. Specialists on each of these provinces have agreed to furnish the data from which such models can be made. After each model is completed it is to be submitted for correction and approval to the geologist supplying the data. A short description is to accompany each model. One model is completed and has the approval of Prof. R. T. Chamberlin. It is desired that teachers of geology study the model, which will be on exhibition, and tell the committee whether or not such models will be useful, and, if so, what modification will add to their usefulness.

No one has been found to construct animated block diagrams for moving pictures, but a moving-picture company has expressed itself as anxious to undertake the production of such films. It is hoped that some competent geological artist will undertake this important work.

A number of models which were illustrated in the last report of the committee will soon be placed on the market by a well-known firm.

It is again recommended that standard collections of lantern slides of geological, physiographical, and paleontological subjects be brought together.

It is further recommended that a method be devised and carried out



G. P. Cox

so that colleges and universities can secure geological specimens for use in teaching. A suggestion has been offered which seems feasible.

NECROLOGY

The Secretary announced the death during the year of five Fellows, all but one of whom were original Fellows of the Society. Brief oral tributes were then given as follows: J. C. Branner, by Bailey Willis; R. D. Salisbury, by N. M. Fenneman, in the absence of T. C. Chamberlin; James E. Todd, by Frank Leverett; Levi Holbrook, by James F. Kemp.

C. L. Dake, who had prepared a written memorial of G. H. Cox, was unable to be present to give his oral tribute.

The written memorials are given in the Proceedings. In addition to the foregoing, a memorial of Joseph Barrell, held over from last year, is included.

MEMORIAL OF GUY H. COX ¹

BY C. L. DAKE

Doctor G. H. Cox, Fellow of the Geological Society, was overturned in his automobile late Saturday night, August 19, 1922, while driving between Bristow and Sapulpa, Oklahoma, and fatally injured. He was taken to the hospital at Bristow, where he died early the following morning, never having recovered consciousness after the accident.

Guy Henry Cox was born at Lehigh, Iowa, May 4, 1881, son of Edward Henry Cox and Ada Wilson. His early education was in the public schools of Fort Dodge, Iowa. In 1905 he was graduated from Northwestern University with the degree of Bachelor of Arts. Following this he did graduate work in the School of Mines of the University of California in 1905-1906.

During the years of 1906-1908 he carried on graduate work at the University of Wisconsin, holding the Fellowship in Geology in 1907-1908. He received the degree of Doctor of Philosophy from that institution in 1911. In 1914 he was granted the degree of Engineer of Mines by the Missouri School of Mines and Metallurgy.

On December 27, 1907, Doctor Cox was united in marriage to Miss Kitty May Gates, of Clear Lake, Iowa, and to them were born two children, Kenneth Dale and Catherine Gates.

Doctor Cox served as instructor in geology in the University of California during the college year of 1908-1909, coming to the Missouri

¹ Manuscript received by the Secretary of the Society November 6, 1922.

School of Mines and Metallurgy as Assistant Professor of Mineralogy and Petrography in 1909. In 1911 he was made Professor of Geology and Mineralogy, and occupied that chair until 1920, when he resigned to go into consulting petroleum geology.

The work of Doctor Cox for the School of Mines is particularly noteworthy for the fine organization of the department that he brought about. He was an ambitious and tireless worker and made his department a recognized force in the school.

Doctor Cox had a wide field experience, beginning in 1904 with a season in southwestern Wisconsin for the Geological and Natural History Survey of that State. The summer of 1906 was spent, under the supervision of Doctor U. S. Grant, with a party in Wyoming. The summer of 1907 was spent in engineering and exploration work in Alaska, including a study of Alaskan tin deposits and also involving extensive sampling of Nome placer deposits.

In 1908 he was engaged with the Wisconsin Survey in the zinc and lead district, and the two following seasons with the Illinois Survey in working out the origin of the lead and zinc deposits of the upper Mississippi Valley. During 1911 he served as engineer for the Wisconsin Zinc Company. This work resulted in the publication of two of his most important contributions to geological literature: "The origin of the lead and zinc deposits of the upper Mississippi Valley district," *Economic Geology*, volume 6, number 5, 1911, and "Lead and zinc deposits of northwestern Illinois," *Illinois Geological Survey, Bulletin* 21, 1914. In these papers he advances the theory that the sulphides of zinc and lead were first deposited from the sea, in disseminated form, in the highly organic Maquoketa shale, and that as this formation was removed by erosion, descending cold solutions redeposited the ores where they now occur.

Doctor Cox also spent one summer prospecting in the vicinity of Trout Creek, Montana. More recently his field activities were devoted almost exclusively to petroleum exploration. These activities began with an extensive trip, designed primarily to secure data on which to build up a course in petroleum geology in the School of Mines. This trip involved visits to Wyoming, California, Texas, Louisiana, Oklahoma, and Kansas. During the college year of 1916-1917 he was on leave and maintained consulting offices in Tulsa, Oklahoma, under the name of Cox & Radcliffe. As a result of his extensive field-work in petroleum geology, he invited the other members of his department to cooperate with him in the preparation of a treatise on "Field methods in petroleum geology," his experience leading him to feel that there was a real place for such a work. This appeared as a McGraw-Hill publication in 1921.

In 1920 Doctor Cox resigned his position in the School of Mines, and from that time until his death he devoted his energies entirely to petroleum exploration, the major part of his work being done in the mid-continent field in Oklahoma, Texas, Kansas, and Arkansas. He was located in Oklahoma City.

Doctor Cox was a member of the Alpha of Wisconsin Chapter of Alpha Chi Sigma, an honorary member of the Beta of Missouri Chapter of Tau Beta Pi, and a charter member of the Missouri School of Mines Chapter of Phi Kappa Phi.

He had belonged to the American Institute of Mining Engineers since 1912; to the American Association of Petroleum Geologists since 1917; to the Society for the Promotion of Engineering Education since 1919, and to the Geological Society of America since 1920.

Not only was Doctor Cox an able teacher, he was also an ambitious and tireless worker and an excellent organizer. He has contributed a number of important papers to the literature of geology and was one of the few men who, in the keen competition of commercial work, kept up his interest in purely scientific problems. Had he been spared he would undoubtedly have contributed much to the further development of our science, contributions rendered especially valuable because guided by the spirit of quantitative precision engendered by engineering practice. He was of the type we can ill afford to lose.

PUBLICATIONS

- Copper in southwestern Wisconsin. Mining and Scientific Press, volume 99, page 529, 1909.
- Lead and zinc district of northern Illinois. Mining World, volume 34, pages 439-442, 1911.
- A new type of Wisconsin zinc deposit. Engineering and Mining Journal, November 30, 1912, page 1040.
- The origin of the lead and zinc ores of the upper Mississippi Valley district. Economic Geology, volume 6, number 5, 1911.
- Lead and zinc deposits of northwestern Illinois. Illinois Geological Survey. Bulletin 21, 1914.
- Methods of prospecting and estimating ore bodies in the Wisconsin zinc and lead district. Thesis for Engineer of Mines degree, Missouri School of Mines and Metallurgy.
- Structureless structure. Oil and Gas Journal, 1917.

JOINT PUBLICATIONS

- Highland, Linden, Mifflin, and Mineral Point topographic and geologic sheets, in Atlas of Bulletin 14. Wisconsin Geological and Natural History Survey, lead and zinc deposits of Wisconsin. (With U. S. Grant, M. J. Perdue, J. R. Banister, and G. H. Cady.)

- Elizabeth sheet of the lead and zinc district of northern Illinois. Illinois Geological Survey, Bulletin 16, 1909.
- Some relations between the composition of a mineral and its physical properties. Missouri School of Mines and Metallurgy, General Series, volume 3, number 1, 1910. (With E. P. Murray.)
- Geologic criteria for determining the structural position of sedimentary beds. Missouri School of Mines and Metallurgy, Technical Series, volume 2, number 4, 1916. (With C. L. Dake.)
- Studies on the origin of Missouri cherts and zinc ores. Missouri School of Mines and Metallurgy, Technical Series, volume 3, number 2, 1916. (With V. H. Gottschalk and Reginald Dean.)
- Field methods in petroleum geology. McGraw-Hill, 1920. (With C. L. Dake and G. A. Muilenburg.)

MEMORIAL OF JOSEPH BARRELL¹

BY HERBERT E. GREGORY

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INTRODUCTION

During the past few years an unusual number of names have been erased from the rolls of the Geological Society—men whom our science can ill afford to spare. From the Yale contingent alone and in seventeen months death has taken three eminent geologists, all in the height of

¹ Manuscript received by the Secretary of the Society November 8, 1922.

Joseph Barrell, born in New Providence, New Jersey, December 15, 1869, was the son of Henry Ferdinand and Elizabeth (Wisner) Barrell. B. S. 1892, E. M. 1893, M. S. 1897 (Sc. D., Honorary, 1916), Lehigh University; Ph. D., Yale University, 1900. Married Lena Hopper Bailey December 27, 1902. Teacher in public schools, 1886-87; instructor in mining and metallurgy, Lehigh University, 1893-97; assistant mining engineer, Lehigh Valley Coal Company, 1894, Butte & Boston, and Boston & Montana mining companies, Butte, Montana, 1897-98; field assistant, U. S. Geological Survey, 1899-1901; assistant professor of geology, Lehigh University, and in charge of Department of Natural Sciences, 1900-03; assistant professor of geology, 1903-08, professor of structural geology, 1908-1919, Yale University. Fellow of the American Association for the Advancement of Science, Geological Society of America, Washington Academy of Sciences, American Academy of Arts and Sciences, Paleontological Society, National Academy of Sciences; member of Connecticut Academy of Sciences. Died at New Haven, Connecticut, May 4, 1919.



Joseph Barrell

their productive power. The loss of Irving, Pirsson, and Barrell is a staggering blow to the geological faculty; it disrupts the team and affects fundamentally the plans for maintaining a strong, well-balanced department. To carry out the program for organized graduate instruction authorized by the university in 1902, Barrell was the first man called, and quickly justified the choice. In the words of Professor Schuchert, "He was a power among us and it was around him that our graduate courses were built."

HISTORICAL SKETCH ²

In Professor Barrell, birth and education appear to have combined to prepare for a distinguished career. Generations of seafaring men and farmers in Normandy, England, Massachusetts, New York, and New Jersey may have contributed a taste for nature and disregard for refinements and superficial views. For Barrell's father one must have the highest admiration. He was an intellectual leader in a country town—a lover of books and of the out-of-doors, a man who interested his children in trees, insects, and stars and directed their reading in serious topics relating to natural history. This man of learning and common sense appears to have been responsible also for outlining the course of training which made up the first three stages of an ideal program of studies. What better course could be devised for a man set aside as a physical geologist than that chosen for and by Barrell: elementary school and high school in a rural village, a year at a city preparatory school, four years of engineering studies, six years of mining practice combined with teaching of mathematics, astronomy, mining, and metallurgy, and capped by two years of graduate study of field and laboratory problems. Few men at the age of thirty-one have built such a broad and solid base for a future scholarly career.

After receiving the doctorate at Yale in 1900, Barrell returned to Lehigh as Assistant Professor of Geology—a position held open for two years through the generosity of Prof. E. H. Williams, Jr. This appointment involved giving special attention to the economic and engineering aspects of the geology and also instructing an elementary class in biology. After teaching three years at Lehigh, Barrell was called upon to make what he would have termed "the critical decision." His life had been planned for a promising career as a mining geologist, with its desirable professional and financial relations. The acceptance of an invitation ex-

² A biography of Barrell which includes much detail of educational and family history, compiled by Charles Schuchert, appeared in the *American Journal of Science* in October, 1919.

tended by Yale College in 1903 to develop the field of structural geology involved almost a right-about-face in purpose and personal contacts. It involved the substitution of a career in engineering and connection with an engineering school for graduate teaching and research in an institution devoted to non-professional training. I well remember the ensuing conversations and correspondence, which were so characteristic of his mental processes. On the one hand, devotion to his Alma Mater and to his friend, Professor Williams, counted for something, and the practical assurance of financial competence for one who had recently married, and who all his life had gone without luxuries, counted for more. On the other hand, he realized that the mining engineer necessarily emphasizes commercial utilization rather than the solution of geological problems, and that uninterrupted time for study and intimate association with minds devoted solely to advancing knowledge offered favorable conditions for finding answers to the many questions which crowded his fertile brain. Fortunately, Barrell chose Yale, and found there the leisure, stimulus, and appreciation which constitute the favorable environment for the play of a powerful intellect.

In the scheme of instruction at Yale, Barrell had charge of two classes: a half-year undergraduate class in historical geology and a full-year course, primarily for graduates in dynamical and structural geology. From time to time as emergencies arose, he took part in teaching classes in field geology, and nearly every year students studying for the degree of doctor of philosophy were grouped by him in a special course in which study of the literature and solution of problems constituted the subject-matter. The decision to relieve Barrell of the multitudinous routine tasks which consume the time of the average professor was amply justified.

Barrell's undergraduate teaching was characterized by systematic planning and orderliness, by logical development of the subject-matter, and by careful choice of essentials. But before the class he was the geologist rather than the teacher of untrained minds. He devoted his attention to the arrangement and presentation of valuable information rather than to perfecting of devices for leading the student to think in geological terms. The informal give-and-take method of elementary instruction was unsuited to his mode of thought. The recognition of the average undergraduate viewpoint played little part in his teaching, and sympathetic personal relations with students were rarely maintained; but a "square deal" was always forthcoming, and evidence is abundant that the method used by Barrell was eminently successful for the better minds in his classes.

While mildly begrudging the time and thought necessarily consumed by even a moderate amount of undergraduate teaching, Barrell persistently clung to his class in historical geology, not only for the joy of presenting truths to interested minds, but because, as he expressed it, "teaching benefits the teacher even more than the taught." That his reasoning was sound is shown by the disappearance of "Old Bathylith" and "Interstitial Relations" as friendly nicknames on the campus. And it is probable that the practice in presenting geological subjects to men unfamiliar with facts and processes and terminology is in large part responsible for the improvement in style revealed in his latest writing.

In graduate teaching, where analytical thought, mental invention, breadth and depth of knowledge make the successful instructor, Barrell had few equals. Few advanced students listened to his lectures without a desire to know more about earth history and processes, and without a feeling of thankfulness for the opportunity to come closely into contact with this exceptional mind. And it is worthy of note that the men who came to Barrell with the most experience and knowledge are the most enthusiastic in their praise. The attitude of the serious, experienced student is well shown in a letter from D. Foster Hewett:

It was my good fortune to have close acquaintance as a student with Professor Barrell, first at Lehigh for three years and later at Yale for two years. In the classroom I feel that his most distinctive characteristics were simple and unaffected bearing, faithful and systematic preparation for his tasks, and orderly and well-balanced use of the class-room period. It is worth while to lay emphasis upon his simplicity, expressed in manner, speech, and dress; for, however natural it may have been, it was also an expression of a profound conviction that the unessential is generally wasteful. Those who knew him outside of the classroom recollect that in advance of each period he systematically prepared outlines for the lecture or recitation. Preserved in notebooks, the outlines furnished the basis for each new year's work. In succeeding years, the course was enriched by his own experience and wide reading. There must be few who were not impressed by the rare facility he showed for making each lecture a well-balanced statement of fact, a development and test of hypothesis, and a summary of conclusions, all fitted nicely to the allotted period. His engineering training was frequently brought out in his facility for using algebra, descriptive geometry, calculus, or analytical mechanics in presenting or testing hypotheses. In his teaching, as in his writing, he emphasized what many students of earth processes overlook—that many of the forces in operation, though commonly of great magnitude, are governed by simple laws of physics. Many will recall his annual lecture on the conditions of deposition of the Newark series. By the use of lantern slides, carefully selected to show the evidence concerning the conditions and fauna of the time, he developed the imaginary vicissitudes and tragedies of the Triassic inhabitants of Connecticut with such rare imagination and keen sense of humor that he rarely failed to bring forth a spontaneous burst of applause.

In seminar periods he showed exceptional capacity for visualizing the student's problem and generosity in contributing time and interest to the serious student. At the monthly meeting of the Dana Club, composed of the graduate students in geology at Yale, he inspired debate with the predetermined purpose of encouraging facility for expression, but if extreme divergence of opinion developed he sought to reconcile the differences.

I can clearly recall several incidents, particularly near Mount Carmel, north of New Haven, when he gave fine exhibitions of grasp of the principle of multiple working hypothesis in the examination of small outcrops of diabase with the view to proving beyond doubt whether they represented masses of surface flows. Many may remember that even Dana did not instinctively understand this process.

A student could scarcely fail to be impressed by the capacity of his intellect, the force of his appeal, the breadth of his interest and sympathetic consideration, and the high mental and physical standards that he set for himself and those who were fortunate enough to be associated with him.

As a teacher of professional geologists, Barrell has received wide recognition. In the many letters of appreciation received from distinguished geologists at home and abroad the expressions "leader," "guide," and "teacher" are common. Certain it is that the analyses, demonstration of method, and evaluation of the literature shown in the writings of Barrell have cleared the way for a more successful attack on problems of stratigraphy and structure.

SOME PERSONAL CHARACTERISTICS

Barrell was a man of strong, unique personality. His ideals were high and his demands for creature comforts small. He cared little for popularity and for the non-essentials which go with social prestige. His great desires were uninterrupted time for work and intellectual fellowship established through writings. He possessed many attractive human traits, but his intellectual power was so obvious and so continuously displayed that twenty years of intimacy has left me an impression of a mind rather than of a man. His personality appeared to be contained in a mind of surpassing fertility, imagination, and machine-like logic. His death marks the loss of a thinker—rare in any generation.

The key words to Barrell's character are "justice" and "logic" rather than "sentiment" and "altruism"; and these dominant mental traits appear even in small affairs.

In playing handball, a game which Barrell put on his schedule, not for the sheer joy of playing, but as a conditioning factor in mental work, disputed points were not to be settled by mutual give and take, but by plotting the course which a ball must have taken to reach a certain point.

He took no advantage, and he gave none; he was meticulously just and carried exactness of method into details of every-day life.

Barrell's unbounded confidence in conclusions reached by reasoning—a quality which yielded such large returns to science—also led him to some odd convictions. No amount of argument and friendly ridicule could convince Barrell that a man of his length and build and weight could learn to swim in fresh water. Likewise a careful study of his family history and insurance tables led to the unshakable belief that some thirty years of active life were ahead of him. And in spite of his naturally kindly disposition and his desire to maintain an open mind, he found it extremely difficult to modify his views of individuals, political tenets, and religious teachings, after a thoughtful decision had once been made.

A striking feature of Barrell's mind was its complete detachment. He used the same criteria in judging his own powers and attainments as those he applied to others. He cared little for adverse criticism and not much more for praise. He felt that work should be measured by abstract standards or, to use his term, "an independent witness," and that questions of friendship and nationality and codes of ethics and modesty have nothing to do with principles and methods. He placed high valuation on his own work, was fond of quoting from himself, and somewhat impatient of those who failed to recognize the worth of his contributions. But in this attitude there was no discernible trace of lack of modesty or undue seeking for personal glory. He thought highly of his opinions and of his publications not because they were his, but because they were good. His clean-cut, detached mind had pronounced a judgment in which we all concur.

METHOD OF WORK

It is interesting and helpful to record the methods used by Barrell in the preparation of his papers. His choice of topics arose partly from personal interest and the needs of his immediate colleagues, but largely from a feeling that investigation in certain fields was prerequisite to progress in geological thought. When chosen, the problem was analyzed and, controlled by multiple hypotheses, a series of deductions was framed, each one of which rested solidly on the assumptions adopted for the purpose. In the form of elaborate outlines, the paper thus made its initial appearance. Then, and usually not till then, was a serious study of the literature made. When, as sometimes happened, a perusal of printed works showed that conclusions similar to his own had previously

been recorded, Barrell laid aside the problem for a time or proceeded with his original plan, on the theory that, as he expressed it, "an independent treatment of any important topic is valuable," and "the results of thinking ought not to be wasted." Geological literature to Barrell was an aid, not a guide, to thinking; but this aid was utilized to the full and in a masterly manner. As Schuchert has remarked, "his best results were obtained through generalizing from the publications of others."

But his criticism of published works, his skill in assembling, testing, and interpreting the field and laboratory observations of others, was of no ordinary sort. T. C. Chamberlin made the remark, "I consider Barrell the best *reader* of geology in America."

For the average mind, this method of substituting the printed page for direct observation and experiment has obvious disadvantages, and the quality of Barrell's mind is nowhere better shown than in the interpretations of processes and structures and formations which he had not seen. The remarkable success of his method, recognized as clearly by him as by others, doubtless accounts for Barrell's neglect of opportunities for extensive field studies in America and abroad.

THE WRITINGS OF PROFESSOR BARRELL

In his writings Barrell shows a surprising range of accomplishment, a firm grasp of the subject-matter of geology lying between the extremes of physical chemistry and biology, and familiarity with the inductive and deductive methods of reasoning. His studies of the Elkhorn and the Marysville mining district, which reveal the mastery of petrography and chemical mineralogy, resulted in the invention of the theory of magmatic stoping, which has played such an important part in the investigations of the processes of igneous intrusion. At the other end of the geological field are his interesting contributions to paleontology and evolution, "the rise of air-breathing vertebrates and the origin of the Tertiary ape-man." Conscious choice and the necessary distribution of labor among the Yale professors led to a centering of interest on dynamical and structural geology—"the center of the geological field," as he termed it; but within this roughly defined area no subdivisions into structure, physiography, erosion, sedimentation, climatology, isostasy, and stratigraphy were recognized. It is probable that Barrell will be valued by future geologists not as a specialist, but as a man who has enlarged the boundaries and strengthened the foundations of what might be called "general geology."

All of Barrell's writings rank with the best and will stimulate thought for many years to come, but the ones which appear to have produced the

greatest influence are his papers on isostasy and those dealing with the origin of continental and littoral sediments. A proper evaluation of these contributions can only come from men who are masters of the subjects.

In response to my request for a statement regarding the character, scope, and significance of Barrell's work on isostasy, Dr. William Bowie has submitted the following:

I wish to take this opportunity of expressing my deep appreciation of the very valuable contribution made to the literature on the theory of isostasy by Prof. Joseph Barrell. His work was far-reaching and thorough and threw much light on the relation of isostasy to geology. In fact, Barrell did more, in my estimation, to bring the geodesists and geologists together in the science of isostasy than did any other investigator. Geodesists deeply feel the loss of Barrell, for they were depending on him to lead thought in the application of the theory of isostasy to geological science.

Barrell's work in isostasy will long be an inspiration to geodesists and geologists and his name will always be associated with those of Pratt, Dutton, Hayford, and others who have made notable contributions to the knowledge of isostasy.

The group of papers which may be termed studies in sedimentation reveal so fully the mental characteristics of Barrell, his methods of thinking, and the results and significance of his contribution that they deserve separate treatment. To supply this need, T. Wayland Vaughan kindly consented to prepare the paper on the work of Professor Barrell in problems of sedimentation.³

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The scientific reputation of Barrell rests on the papers listed below. A complete list of titles would include 19 reviews, chiefly in the general field of geophysics, 5 brief discussions of papers read before the Geological Society of America, 3 abstracts of papers later published in full, and 4 contributions of local university interest.

As arranged chronologically, Barrell's bibliography shows a development of interest in the broad aspects of geology, and also the influence of changed surroundings and associations. The engineer and mining geologist is revealed in the papers published before 1906 and also in the "Geology of the Marysville Mining District," which, though published in 1907, is based on field-work done some years previously. After adjusting himself to his routine work at Yale, Barrell entered whole-heartedly

³ Bull. Geol. Soc. Am., this volume, pp. 28-44.

⁴ For a complete bibliography of Professor Barrell, see Schuchert, loc. cit., pp. 277-280.

into the investigation of sediments with particular reference to climatic influences, and his papers bearing dates 1906-1914 show a decided change from the viewpoint and the precise methods of the engineer and petrographer. Another change of emphasis is shown in the publication of the series of papers on the strength of the earth's crust, in 1914-15. In the publications since that time Barrell's two absorbing interests, origin of sediments and geophysics, are about equally represented. The bibliography includes no titles which would ordinarily be classed as popular articles. The nearest approach are the five papers which appeared in 1917-1919, and it is significant to note that these contributions were the response to definite local requests.

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THE WORK OF JOSEPH BARRELL ON PROBLEMS IN SEDIMENTATION ¹

BY THOMAS WAYLAND VAUGHAN ²

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PROBLEMS IN SEDIMENTATION CONSIDERED BY BARRELL

The best way quickly to gain a correct idea of that part of the field of sedimentation in the study of which Barrell was active is to give the following list of his papers on the subject:³

1906. Relative geological importance of continental, littoral, and marine sedimentation. *Journal of Geology*, volume 14, pages 316-356, 430-457, 524-568.
 1907. Review of "Manual of the geology of Connecticut," by W. N. Rice and H. E. Gregory. *American Journal of Science*, fourth series, volume 23, pages 385-392.

¹ Manuscript received by the Secretary of the Society November 8, 1922.

² Published by permission of the Director of the U. S. Geological Survey.

³ Taken from list by Charles Schuchert. *Am. Jour. Sci.* (4), vol. 48, 1919, pp. 277-280.

- Origin and significance of the Mauch Chunk shale. *Bulletin of the Geological Society of America*, volume 18, pages 449-476. Abstract in *Science*, new series, volume 25, page 766.
1908. Relations between climate and terrestrial deposits. Part I, Relations of sediments to regions of erosion. *Journal of Geology*, volume 16, pages 159-190. Part II, Relation of sediments to regions of deposition. *Ibid.*, pages 255-295. Part III, Relations of climate to stream transportation. *Ibid.*, pages 363-384. Abstracts in *Science*, new series, volume 25, 1907, page 766; and *Bulletin of the Geological Society of America*, volume 18, 1906, pages 616-621.
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- 1913-1914. The Upper Devonian delta of the Appalachian geosyncline. Part I, The delta and its relations to the interior sea. *American Journal of Science*, fourth series, volume 36, pages 429-472. Part II, Factors controlling the present limits of the strata. *Ibid.*, volume 37, pages 87-109. Part III, The relations of the delta to Appalachia. *Ibid.*, pages 225-253.
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1916. Discussion of paper by R. W. Sayles on "Banded glacial slates of Permocarboniferous age, showing possible seasonal variations in deposition." *Bulletin of the Geological Society of America*, volume 27, pages 112-113.
Dominantly fluvial origin under seasonal rainfall of the old red sandstone. *Ibid.*, volume 27, pages 345-386. In shorter form in *Proceedings of the National Academy of Science*, volume 2, pages 496-499.

1917. Rhythms and the measurements of geologic time. *Bulletin of the Geological Society of America*, volume 28, pages 745-904.

From this list it is evident that his personal research was limited in its scope, and that it was devoted almost entirely to continental and littoral sediments. In his studies of delta deposits he considered some marine sediments. Otherwise, except in an incidental manner, he scarcely discussed marine deposits until it became necessary for him in his paper, "Rhythms and the measurements of geologic time," to devote more attention to them, and he did not then add to knowledge of the origin and classification of marine deposits. Barrell's rough estimate of the area now covered by "the subaerial deposits of piedmont waste, of continental basins, and of deltas" is one-tenth of the emerged continental surfaces, and that "adding this to the estimate of the deposits of arid climates would give a fifth of the land surface as mantled by continental deposits."⁴ Although this ratio was not persistent throughout the different geologic epochs, the question logically raises itself, Why did he devote so large a part of his energies to deposits that occupy relatively so small a part of the earth's surface? The answer to this question may be found in his early environment and in the geologic problems he there encountered, for they cast over him a spell that was never broken.

When Barrell was only five years old his father bought a farm at New Providence, New Jersey, and there Joseph made his home until he grew to manhood. New Providence is situated in the Triassic belt of New Jersey, on the outcrop of the Brunswick formation, the uppermost of the three formations that compose the Newark group in that district. In this connection it is interesting to note that there are in Barrell's writings frequent reference to the Triassic deposits of the eastern United States, and that he clearly had an extensive first-hand familiarity with them.

When nineteen years old Barrell went to college at Lehigh, in South Bethlehem, Pennsylvania. South Bethlehem is not actually within the district from the study of which Barrell was later to make himself famous, but it is situated near the eastern edge of the outcrop of the Ordovician formations, and he subsequently needed to use all the knowledge he could command of that part of the Appalachians. His work for his master's degree familiarized him with the Archean Highlands of New Jersey and their extensions into New York and Pennsylvania, but he found his big problem in the Anthracite region, where he practiced mine surveying with students after he became an instructor at Lehigh in 1893.

⁴ *Jour. Geol.*, vol. 14, 1906, p. 355.

Barrell was evidently impressed by the features of certain formations with which he became familiar during this period of his life; these formations were the Triassic deposits, the Mauch Chunk shale, and the overlying Coal Measures, the Pocono sandstone, and the deposits of the Catskill group. The current interpretations of the conditions under which and the processes by which these deposits were formed did not satisfy him. Furthermore, there were the great problems of the formation of the geosynclines in which the deposits were laid down, the former extension of the deposits, and the sources of the materials composing the deposits, all of which led to the consideration of the orographic history of the northern Appalachians and their degradation and the origin of the Continental Shelf of eastern North America. The experiences in eastern and central Pennsylvania unfolded to Barrell problems to the solution of which he assiduously set to work.

BARRELL'S INVESTIGATIONS OF THE PRINCIPLES OF SEDIMENTATION

GENERAL OBSERVATIONS ON BARRELL'S WORK

The first paragraph in the second one of Barrell's longer papers on sedimentation, "The origin and significance of the Mauch Chunk shale," is as follows:

"A discussion of the nature of geographic and climatic control of sedimentation has been previously made by the writer in order that the origin of certain specific formations might be dealt with, and the present paper on the interpretation of the Mauch Chunk follows these previous articles in logical sequence."⁵

A quotation from the article referred to in the footnote is as follows:

"As pointed out by Walther in 1893, although all geologists are familiar with the occasional extensive deposition of land-waste upon the land as among the results of geological activities at the present time, yet the prevalence of erosion on the land and of sedimentation beneath the sea has governed the interpretation of nearly all ancient sedimentary deposits. It has ordinarily been accepted as a geological principle, that ancient continental surfaces are only determined by unconformities, while, on the other hand, all sediments, unless obviously deposited by fresh waters, as proved by their organic contents, are taken as indications of the presence of ancient seas.

"As showing exceptions to this tendency to neglect the deposits formed upon the land must be noted the work of the geologists of the Indian Survey for the past thirty years, and that of other geologists who have been most familiar with the Tertiary and Recent deposits within the interiors of Asia and America."

⁵ Relative importance of continental, littoral, and marine sedimentation. Jour. Geol., vol. 14, 1906, pp. 316-356, 430-457, 524-568.

Barrell, after recognizing that the characteristics of certain important geologic formations were not compatible with what was known of the features of marine sediments, undertook a comprehensive study of the characteristics of continental and littoral deposits, the only other classes of deposits to which they could belong. He worked mostly by compilation from literature and by deduction from well established principles, but he made a few simple experiments on the formation of mud-cracks. In many respects his work was not so detailed as desirable. For instance, he gave no mechanical analyses of the sediments studied, sorting is discussed in only a general way, and more attention might profitably have been paid to the mineralogic and chemical composition of sediments. He himself recognized and mentioned these deficiencies, thereby offering guidance to further studies in many of the important problems in sedimentation.

It is practicable in a brief review, such as this necessarily is, merely to indicate some of the important results of Barrell's studies, and it should be stated in fairness to others that many others had prior to Barrell done more or less work along similar lines: but to him belongs the credit of assembling scattered observations and conclusions, organizing them into a consistent body of usable criteria, and applying these criteria to the interpretation of many formations. Certain factors in the control of sedimentation and certain distinctive features of some kinds of sediments will be briefly discussed, the remarks being based on his principal articles. Reviews by him and his discussions of papers by others are not considered, because to do so would unluly extend the length of this statement.

THE RELIEF FACTOR IN DEPOSITION

A concept of fundamental importance in the consideration of problems of sedimentation is that of baselevel. That there is a terrestrial baselevel, the goal toward which all erosional agencies on the land are working, and that there is a marine baselevel, which is effective wave base, toward which marine agencies are working, have long been recognized, but they had not been sufficiently considered in their relations one to the other. Barrell says:

"Thus sediments whose interpretation from [sic] the basis of earth history have been characteristically deposited with respect to a nearly horizontal controlling surface. This surface of control is baselevel, but for continents and marine deposits the baselevel is determined by different agencies and is a word of more inclusive content than the sense in which it has generally been used by physiographers as a level limiting the depth of fluvial erosion. Sedimentation as well as erosion is controlled by baselevel, and baselevel, local

or regional, is that surface toward which the external forces strive, the surface at which neither erosion nor sedimentation takes place.”⁶

Any change in the surface of the lithosphere that causes a change in the position of the land surface or of the sea-bottom with reference to baselevel will obviously produce corresponding changes in sedimentation. Barrell states a principle accepted by most geologists, although he considered it desirable to present the evidence on which it is based, as follows:

“The rate of denudation increases through the stage of topographic youth, reaching a maximum when all of a drainage basin has become dissected and given a maximum of sloping surface. From this mature stage the rate decreases as the elevation of the interstream areas are lowered, and finally nearly ceases in topographic old age.”⁷

Firmly grasping this principle, the characteristics of continental deposits are discussed.⁸ He classifies these as follows:

“Formations made upon the land may be classified under several divisions, as follows:

“*Desert deposits*.—Typically where the evaporation exceeds the precipitation and no outflowing drainage results.

“*Piedmont river deposits*.—Built up by rivers or shallow lakes upon the foreland plains or piedmont belt fronting high mountain ranges.

“*Basin deposits of pluvial climates*.—The deposits laid down by rivers or in lakes in down-warped basins, such as those of the Great Lakes, situated in continental interiors, but not necessarily associated with mountains. If a large river, laden with sediment, flows across such a region, a lake condition can hardly arise, but, on the contrary, a broad river plain is more likely to be found, constantly built up as subsidence takes place.

“*Subaerial delta deposits*.—Where powerful and sediment-laden rivers meet the sea, especially if the latter is shallow and protected from tides and storms, a delta is rapidly developed, a considerable portion of which is a land surface reclaimed by the river from the sea.”⁹

Each of these classes of deposits is discussed with reference to its stage in the physiographic cycle, but the conclusions can not be summarized in this place.

The effect of both orogenic and epeiric crustal movement on sedimentation are discussed in considerable detail, particularly in his “rhythms

⁶ Rhythms and the measurements of geologic time. Bull. Geol. Soc. Am., vol. 28, 1917, p. 778.

⁷ Op. sup. cit., p. 756.

⁸ Illustrative quotations are not in chronologic order, for it can be inferred from Barrell's writings that conclusions had been definitely reached and were being utilized by him before he actually expressed them in the words best adapted for purposes of quotation.

⁹ Relative geological importance of continental, littoral, and marine sedimentation. Jour. Geol., vol. 14, 1906, pp. 328, 329.

and the measurements of geologic time," pages 753-809, where it is convincingly shown that because of tectonic movements in late Tertiary and Pleistocene time and the consequent high stand and great relief of the continents, the rate of erosion, and correlatively the rate of sedimentation, far exceeds the average rate of erosion and sedimentation of earlier geologic time, "ten or fifteen times the rate for all of geologic time since the opening of the Paleozoic."

Under the caption "Rate of sedimentation determined by subsidence,"¹⁰ Barrell emphasizes a geologic relation that deserves noting. In connection with the recognition of the control of baselevel over both erosion and deposition, it is stated that "on the surface of deltas or the floors of epeiric seas sedimentation records the rate of subsidence, not the rate nor the amount of denudation." The subsidence in general is not due to the load of sediments. "It may readily be granted that this load of sediment, acting in the same direction as the forces initiating subsidence, would tend to continue it and carry it to greater depths; but without the sediments, deep water would almost surely have resulted, such as exists at present in the southern part of the Gulf of California, a geosyncline filled only at its northern end."

THE CLIMATIC FACTOR IN DEPOSITION

One of Barrell's longest papers on problems of sedimentation is entitled "Relations between climate and terrestrial deposits."¹¹ In the general introduction to this series of articles he says:

"The environment of the lands may be classified into three fundamental and independent factors—the relations to the surrounding seas, the topography which forms their surfaces, and the climates which envelop them—each of major importance in controlling the character of the lands and the evolution of their inhabitants.

"The third great problem of terrestrial environment, the succession of ancient climates, lags still farther behind in development, but is no less important in a complete understanding of the history of the earth and its inhabitants. This lack of development is doubtless due to the intangible nature of climate and the absence of direct record of its geologic changes. When it is considered, however, how fundamental are the relations of continental deposits to the climates in which they are formed, it is seen that the record of geologic climates, while indirect and largely awaiting interpretation, is nevertheless in existence.

¹⁰ Rhythms and the measurements of geologic time. Bull. Geol. Soc. Am., vol. 28, 1917, pp. 785-789.

¹¹ Jour. Geol., vol. 16, 1908, pp. 159-190, 255-295, 363-384.

" . . . climate is a factor comparable to disturbances of the crust or movements of the shoreline in determining the nature and the variations in the stratified rocks of continental or offshore origin, thus playing a part of large, though but little-appreciated, importance in the making of the stratigraphic record."

As it is quite impracticable to summarize in this place this excellent study, only the divisions of the subjects will be given and a few general remarks made. Part I is entitled "Relations of sediments to regions of erosion," and in it are discussed the "character of rocks supplying sediment," "relations of rainfall and topography to erosion," "relations of temperature and topography to erosion," "separation of the topographic and climatic factors," and "separation of tectonic and climatic oscillations." Part II is entitled "Relations of sediments to regions of deposition," and in it are considered the "influence of nature of surface of deposition" (piedmont slopes and aerial deltas, lower floodplains and aqueous deltas, and criteria for the elimination of local geographic factors), and the "climatic influences in regions of deposition." Under the latter caption attention is paid to the effects of constantly rainy climates, intermittently rainy climates, semi-arid climates, and arid climates, and to the climatic significance of color. Part III is devoted to the "Relations of climate to stream transportation." In this part the topics discussed are "the effects of stream transportation," "relations of stable climates to transportation," and "effects of varying climates upon transportation."

These topics can only give an idea of the treatment of the subject. One climatic relation of special importance will be mentioned. Barrell describes in the third part of this article how the piedmont slopes built up in the youth of a normal topographic cycle would be trenched and the removal of the component materials commence in a stage of maturity. If there were in topographic maturity a sudden change from semi-arid to pluvial climate, erosion of the piedmont slopes will be accelerated and "the final region of deposit undergo a sudden increase in sedimentation, which may be called a veritable flood of waste, but it will be of phenomenal coarseness compared to that which preceded and that which will come after."¹² Conglomerates and sandstones are classified into marine, tectonic, and climatic. He says:

"Climatic conglomerates and sandstones are here made distinct and independent from those of tectonic origin by the taxonomic elevation of the *shifting location* of deposits (in space) to coordinate importance with *intermittent* uplift and resulting pulses of erosion (in time)."¹³

¹² Op. cit., pp. 371, 372.

¹³ Op. cit., p. 384.

RESTORATION OF THE FORMER LIMITS OF GREATLY ERODED FORMATIONS

There has been a tendency among paleogeographers to draw the original boundaries of geologic formations not far from the present limiting outcrops. Because of the existence of detached outliers and because of the evidence of the superposition of drainage lines, as Davis showed to be the case in New Jersey, the original boundaries of some formations have been indicated as lying some distance from the present outcrops of the main bodies of the formations. Barrell in his paper, "The Upper Devonian delta of the Appalachian geosyncline," presented additional criteria for ascertaining the approximate limits of formations that have undergone great erosion. One section of this article is devoted to showing that, except on the borders of fault troughs, there is no necessary structural relation between the present and the original limits of formations, therein taking issue with Willis's opinion on initial dips and the original limits of formations. The additional criteria adduced by Barrell are derived from the character of the sediments of the marginal outcrops and the rate of thinning at the present margins. If continental clastic sediments show by the rounding of pebbles and by gradual reduction in size of pebbles away from the source of the constituents, thereby indicating transportation for long distances, it is obvious that the original margin of the formation lay nearer the source of supply of the sediments than does that part of it still preserved. Deductions from rate of thinning of sediments as to the position of the original boundary rest upon the assumption that "the thinning shown near the present margin continued uniformly to original limits—an assumption which certainly is not exactly true, but which on the other hand serves as an approximation."

THE SIGNIFICANCE OF SOME SPECIAL FEATURES OF SEDIMENTS

Barrell repeatedly emphasized that really sound conclusions on the origin and conditions of deposition of sediments should result not from a single line of evidence, but from the convergence of several independent lines. However, a few special features of importance in interpreting continental deposits will be mentioned.

The most favorable conditions for the formation and preservation of mud-cracks are undoubtedly floodplains that are subjected to periodic overflow and on which are made deposits of non-calcareous clay alternating with somewhat coarser material. Although Barrell gave his first comprehensive discussion of the significance of mud-cracks in 1806,¹⁴ the subject is brought up again and again in his later papers. He says:

¹⁴ Relative geological importance of continental, littoral, and marine sedimentation. Jour. Geol., vol. 14, 1906, pp. 524-568.

"It would seem that next to coal beds formed *in situ*, or abundance of land fossils belonging to the animal kingdom, that mud-cracks form one of the surest indications of the continental origin of argillaceous deposits."¹⁵

The significance of mud-cracks, and also of rain-prints and rootmarks, is entirely convincing when developed, both *broadly* and *vertically* through mechanical sediments."¹⁶

From a study of the conditions most favorable for the production of thick conglomerate formations,¹⁷ Barrell concluded that continental conglomerates exceeded marine conglomerates in importance. He says:

"A maximum limit to widespread basal marine conglomerates seems to be 100 feet, and therefore broad conglomerate formations of greater thickness are evidence of terrestrial accumulation."¹⁸

Minor features indicating marine or river action is pointed out. For instance, he says:

"W. D. Johnson pointed out that in the Tertiary deposits of the High Plains the gravel courses, where exposed to observation, are greatly elongated in the direction of the streams—that is, in the direction leading away from the source of supply. Mansfield has noted that shore gravels, on the contrary, are extended in courses parallel to the margin of the deposit."

He also says:

"River gravels are shingled by the currents, so that the longer diameter of the pebbles dip upstream, giving a faint appearance of false bedding, which on the average, unlike the false bedding of sandstone strata, dip toward the basin margin. Shore gravels, on the other hand, are developed parallel to the shore. The onshore waves have a greater force than the undertow and the shingling dips away from the shore, or runs out laterally from protruding headlands."¹⁹

The color of rocks, particularly with reference to the continental deposits, was discussed in considerable detail by Barrell. He says:

"Such a relation of red shales and gray or green sandstones may then be taken as presumptive evidence of subaerial deposition. It should not, however, be taken by itself as positive evidence, as the number of cases studied on which the conclusion rests is still somewhat limited."

And regarding lateral and vertical variegations in clays, he says:

"Such variegated beds are then highly suggestive of terrestrial deposition,

¹⁵ Op. sup. cit., p. 550.

¹⁶ Am. Jour. Sci. (4), vol. 36, 1914, p. 438.

¹⁷ Some distinctions between marine and terrestrial conglomerates. (Abstract.) Science, n. s., vol. 29, p. 624; Bull. Geol. Soc. Am., vol. 20, 1910, p. 620.

¹⁸ Am. Jour. Sci. (4), vol. 36, 1914, pp. 439, 440.

¹⁹ Bull. Geol. Soc. Am., vol. 27, 1916, p. 357.

and indicate, furthermore, a large development of swamp and pond conditions under a normally humid climatic condition.”²⁰

One thesis in regard to the red color of some rocks defended by Barrell will be noted. He says regarding ferric oxide, to which the red color of sedimentary rocks is due:

“Spontaneous dehydration, assisted by heat and favored by time, does not appear, however, to be the sole cause of the great contrast in color between the consolidated and the surfical ferruginous sediments. A still more potent cause exists in the dehydration effected by the great increase in pressure and moderate rise in temperature which take place upon the burial of the material to some thousands of feet beneath later accumulations.”²¹

The presence of feldspar particles in sediments that have been transported considerable distances is advanced as evidence of a semi-arid climate, for it “indicates a notable degree of physical, as contrasted to chemical, weathering in the regions of erosion.”²² This criterion is a decidedly valuable one.

He says:

“An examination of the character of the matrix or associated fine beds is of importance in determining the climatic conditions attending the origin of a terrestrial conglomerate or sandstone. . . . The character of this fine fluvialite or wash detritus *in the region of its origin* may, therefore, be taken as an index of climate. The size or abundance of the coarser material, on the other hand, forms a measure of the rapidity of erosion, and roughly of the degree of topographic relief.”²³

As a part of Barrell’s studies of the value of criteria, it will be noted that he dissented from certain of Grabau’s opinions regarding the value of overlaps. He says:

“From these examples it is seen that overlap away from the source of supply can not be used as a criterion of continental or marine origin, any more than transgressive or regressive overlap, but may be due to regional subsidence or tilting or a climatic change which shifts clastic material of a certain kind progressively farther from the source of supply.”²⁴

THE INTERPRETATION OF PARTICULAR GEOLOGIC FORMATIONS

Barrell worked from the concrete to the abstract and from the abstract to the concrete. He began by the consideration of specific phenomena.

²⁰ Bull. Geol. Soc. Am., vol. 23, 1912, pp. 422, 423.

²¹ Jour. Geol., vol. 16, 1908, p. 288.

²² Origin and significance of the Mauch Chunk shale. Bull. Geol. Soc. Am., vol. 18, 1907, p. 470.

²³ Jour. Geol., vol. 16, 1908, p. 182.

²⁴ Criteria for the recognition of ancient delta deposits. Bull. Geol. Soc. Am., vol. 23, 1912, p. 395.

For the interpretation of these he sought similar phenomena which were produced under known conditions, and knowledge of fundamental principles, and he then returned to the problem that he at first had in mind. Barrell's investigations of a few formations will be briefly reviewed.

In his first lengthy paper, under the caption "Illustrative geological application,"²⁵ he discussed the mud-cracked geologic formations of the Precambrian of Montana and Arizona and concluded that considerable portions of the Belt terrane and the Grand Canyon series are continental deposits.

The Gila conglomerate of Arizona²⁶ was considered by Barrell as possibly due to climatic causes, for "An examination of the literature showed that the relations of the two divisions of the Gila conglomerate, the volumes and relative ages of each, corresponded with the two epochs of glaciation which were pronounced in Utah and Nevada and the two periods of expansion of Lakes Bonneville and Lahontan." It appears to have "originated from an increase in the ratio of erosion to transportation, due to the severe cold and consequent frost action of the Glacial times, without a correspondingly large increase, in this arid region, of precipitation."

The origin of the "Orange Sand" formation of Hilgard or the "Lafayette" formation of Hilgard and McGee is discussed and the hypothesis is advanced that it may be due to a climatic cause, by a shift from a semi-arid to a rainy climate, as had been indicated on preceding pages of this review.²⁷

The Mauch Chunk shale, for the interpretation of which the studies recorded in the article above referred to were made, "in the anthracite region, more surely in the southeastern and eastern portions," is shown to be, from top to bottom, "a subaerial delta deposit laid down under a semi-arid climate."²⁸

The Patuxent, Arundel, Patapsco, and Raritan formations of the Atlantic Coastal Plain are interpreted as deltas which "were confluent as a flat piedmont coastal plain, probably with a highly irregular and shifting shoreline."²⁹

Barrell's most extensive studies of any set of formations were those of "The Upper Devonian delta of the Appalachian geosyncline,"³⁰ and

²⁵ Jour. Geol., vol. 14, 1906, pp. 353-568.

²⁶ Jour. Geol., vol. 16, 1908, pp. 173-174.

²⁷ Op. sup. cit., pp. 373-378.

²⁸ Bull. Geol. Soc. Am., vol. 18, 1907, p. 450.

²⁹ Bull. Geol. Soc. Am., vol. 23, 1912, p. 410.

³⁰ Am. Jour. Sci. (4), vol. 36, 1913, pp. 429-472; vol. 37, 1914, pp. 87-109, 225-253.

these represent the climax of his interpretative researches on sedimentary formations. Nearly all of his antecedent work on sediments led up to this masterpiece, and out of it grew another masterpiece, his papers bearing the general title "Strength of the earth's crust."³¹ He says regarding the Upper Devonian delta:

"The Portage and Chemung are seen to be the shallow sea equivalents of the Oneonta and Catskill, a subaqueous top set plain. The Skunnemunk conglomerate is a down-folded remnant of a piedmont alluvial gravel plain which lay between the flat delta surface and the mountains. The Pocono sandstone, into which the Catskill passes by transition, is seen to be divided into two phases—a marine phase in western Pennsylvania and Ohio, a fluvatile phase in eastern Pennsylvania. In the Pocono the sharp delimitation of the two phases is obscure, but between the Catskill and Chemung the color contrast draws the dividing line separating the subaerial and subaqueous topset beds. The margin of the delta no doubt held lagoons varying from brackish to fresh water, so that marine fossils should be somewhat more restricted in their range than the gray and olive shales."³²

"The red shale formations, the Catskill and the Mauch Chunk, show transitions on the east into the overlying formations. The Pocono, on the contrary, passes abruptly at its top into the Mauch Chunk shale. Both the Pocono and Pottsville conglomerates are made up dominantly of much water-worn white quartz pebbles, and their whole areas are characterized by a great dominance of siliceous over argillaceous contents. All of these features correspond to the theoretic results upon a broad piedmont slope of increasingly wide swings of the climatic pendulum which carried the world from Upper Devonian warmth and semi-aridity to Upper Carboniferous humidity and possible coolness."³³

As regards the former extent of the Upper Devonian delta deposits and the source of the material composing them, Barrell says:

"The margins of the gravel plain may therefore be estimated at perhaps from 20 to 35 miles to the southeast of the Green Pond syncline, making the original limits of the Upper Devonian deposits from 45 to 60 miles southeast of the present outcrops in Pennsylvania. . . . The distance to the north-western edge of the crystalline floor concealed beneath the Coastal Plain is now about 65 miles, and from beyond this line it would appear that the greater portion of the quartzite must have been derived."

The site of the source of most of the sediments forming the Upper Devonian delta is now the Atlantic Continental Shelf, or even farther seaward, for a source must have existed for 63,000 cubic miles of material.

The Triassic deposits of New Jersey and Connecticut are mentioned in many of Barrell's papers, and their origin is particularly considered

³¹ *Am. Jour. Sci.* (4), vol. 37, 1914, p. 250. See footnote.

³² *Am. Jour. Sci.* (4), vol. 36, 1913, p. 465.

³³ *Am. Jour. Sci.* (4), vol. 37, 1914, pp. 241, 242.

in his "Central Connecticut in the geologic past."³⁴ His opinion was that the sediments were deposited from the waters of migrating rivers and shifting lakes, and that the sediments of the wide river floodplains were subjected to periodic drying. The climate was inferred to be of semi-arid character.

Another group of formations that engaged Barrell's attention was that known as the Old Red Sandstone in the British Isles, and his last important paper on the interpretation of geological formations was entitled "Dominantly fluvial origin under seasonal rainfall of the Old Red Sandstone."³⁵

The conclusions reached in this study are stated as follows:

"The central conclusion reached in this paper is that the Old Red Sandstone formations were not deposited in lakes or estuaries, nor are they of desert origin. The analysis of their characteristics and comparison with sediments now forming determine them to be river deposits accumulated in intermontane basins. This is a kind of sedimentation not now found in the British Isles. For a close analogy one may turn to the basin deposits of the western United States laid down in the Tertiary period between the growing ranges of the Cordillera. This reinterpretation of the Old Red Sandstone of the British Isles is in line with that which has gone forward in America during the past fifteen years in regard to the origin of the continental Tertiary deposits: once looked on as deposited in lakes greater in area than any now existing on the earth, they are now regarded as accumulations made chiefly on river plains. Such a reinterpretation for the Old Red Sandstone involves radical changes in the conception of Devonian geography—no less a change than the substitution of land surfaces, occasionally flooded, as a replacement in the mental vision of wide and permanent bodies of water. If the new interpretation is well founded, it means that such terms as 'Lake Caledonia' and 'Lake Orcadie' should be turned into 'Caledonian and Orcadian basins.'"³⁶

RHYTHMS AND THE MEASUREMENTS OF GEOLOGIC TIME

The title of this section of this review is that of the one of Barrell's papers³⁷ in which he probably attained his greatest height as thinker on fundamental geological problems. A part of it was presented under the title "The significance of sedimentary rhythms," as one of a series of papers composing a "Symposium on the interpretation of sedimentary rocks," at the meeting of the Geological Society of America in Albany, New York, December 29, 1916. It is not practicable to give in this place even an adequate review of this remarkable memoir; a few comments and

³⁴ Connecticut State Geological and Natural History Survey, Bull. 23, 1915, pp. 28-32.

³⁵ Bull. Geol. Soc. Am., vol. 27, 1916, pp. 345-386.

³⁶ Op. cit., pp. 348, 349.

³⁷ Bull. Geol. Soc. Am., vol. 28, 1917, pp. 745-904, pls. 43-46.

quotations must suffice. The work should be studied by all interested in the fundamentals of geology.

Barrell's studies of rhythms affecting sedimentation have been indicated in the discussions of his researches on the relief factor and climate factor in deposition. The first paragraph in his "Rhythms and the measurements of geologic time" is as follows:

"Nature vibrates with rhythms, climatic and diastrophic, those finding stratigraphic expression ranging in period from the rapid oscillation of surface waters, recorded in ripple-marks, to those long-deferred stirrings of the deep imprisoned titans which have divided earth history into periods and eras. The flight of time is measured by the weaving of compositive rhythms—day and night, calm and storm, summer and winter, birth and death—such as these are sensed in the brief life of man. But the career of the earth recedes into a remoteness against which these letter cycles are as unavailing for the measurement of that abyss of time as would be for the measurement of human history the beating of an insect's wing. We must seek out, then, the nature of those longer rhythms whose very existence was unknown until man by the light of science sought to understand the earth. The larger of these must be measured in terms of the smaller, and the smaller must be measured in terms of years. Sedimentation is controlled by them, and the stratigraphic series constitutes a record, written on tablets of stone, of these lesser and greater waves of change which have pulsed through geologic time."

The paper is divided into six parts, as follows: I, Rhythms in denudation; II, Rhythms in sedimentation; III, Estimates of time based on geologic processes; IV, Measurements of time based on radioactivity; V, The age of the Llano series, Texas; VI, Convergence of evidence on geologic time and its bearings.

In Part I it is shown that, because of the present relatively high stand of the continents, the rate of denudation is probably far in excess of the average for geologic time—"the present mean rate may be twice the mean for the whole of the Cenozoic and 10 or 15 times the rate for all of geologic time since the opening of the Paleozoic."³⁸ From this it follows "that time is far longer than those estimates which have been based on a hypothesis that the present rate is a mean which applies to the geologic past."³⁹

In Part II particular emphasis is put on breaks in the continuity of deposition. The word *disconformity* is applied according to current usage, but for cessations of minor magnitude in deposition the term *diastem* is proposed. The admission of the great importance of lost intervals in deposition destroys the basis "for estimating the time of the

³⁸ *Op. cit.*, p. 776.

accumulation of the whole formation by means of an assumed rate of continuous denudation and corresponding sedimentation.”³⁹

In Part III several estimates of geologic time are critically reviewed with reference to “the relations of methods to results and the assumptions on which those methods rest.” Estimates by Lyell, Croll, Kelvin, Sollas, Walcott, Goodchild, Becker, and others are discussed. A fundamental error in many of these estimates lies in the assumption of continuous erosion and continuous deposition at present rates. This assumption invalidates the age estimates by Becker based on the present sodium chloride content of the ocean. These estimates are, therefore, too low. Goodchild’s estimate of 704,000,000 years since the beginning of the Cambrian is considered of the proper order of magnitude. Becker’s estimate of the age of the earth from a combination of data based upon the supposed “curve of fusion of diabase with respect to pressure,” the temperature gradient of the earth according to increase in depth, data on isostasy, and data on radioactive minerals is severely criticized in these words: “Thus, assumption is built on assumption into a many-storied structure and the whole rests on a foundation of quicksand.”⁴⁰

Part IV consists of a careful review of the subject of radioactive minerals in their bearing on the age of the earth. Accumulation of helium, pleochroic halos, and accumulation of lead are discussed in considerable detail. Barrell’s data are taken from Rutheford, Ellen Gleditsch, Arthur Holmes, Ramsay and Soddy, Strutt, Boltwood, and others. The helium ratio indicates an age of 623 to 715 million years as the age of the Lower Precambrian of Renfrew County, Ontario, Canada; but all that this ratio tells is that “the age of a mineral is greater than a certain minimum value.”⁴¹ The lead ratio indicates an age for the larger helium ratio above given as 1,500 million years.

In Part V it is shown that Becker’s conclusions on the uranium minerals from the pegmatite dikes of the Llano series, Texas, are unjustified, and that after eliminating certain analyses for specific reasons, the others serve “as a reliable means of measuring the age of the Llano series and add their weight to the value of the method.”⁴²

In Part VI the different lines of evidence are brought together and on pages 884 and 885 a new table of geologic time is presented. The beginning of Cambrian time is given as between 550 and 700 million years ago; Mesozoic, between 135 and 180 million years ago; Cenozoic, between

³⁹ Op. cit., p. 798.

⁴⁰ Op. cit., p. 841.

⁴¹ Op. cit., p. 847.

⁴² Op. cit., p. 871.

55 and 65 million years ago. Certain Precambrian formations are as old as 1,400 million years, and before this the earth had a long and complicated history. "The depths of geologic time leave us face to face with the unknown."⁴³

CONCLUSION

Although Barrell worked on several different aspects of geology, there was one fundamental, dominant note in all he did. He was primarily striving at the elucidation of the history of the earth. His early training as an engineer supplied him with an appropriate foundation in mathematics, physics, mechanics, and astronomy and impressed upon him the engineer's aim for quantitative, not merely qualitative, expression. Barrell studied sedimentation, but he did not stop with ascertaining the conditions under which certain formations were deposited. He undertook on one hand a study of the strength of the earth's crust, the constitution of the interior of the earth, the age of the earth, and the origin of the earth and the solar system. On the other hand he sought to trace the effects of physical agencies on the evolution of organisms. It was, therefore, not so much because of this one thing or that one thing that Barrell is preeminent: it was rather because he grasped many things and by his powerful synthetic mind focused them on the great problems of earth history, and made contributions so monumentally important that he justly deserves appraisal as one of the world's great geologists.

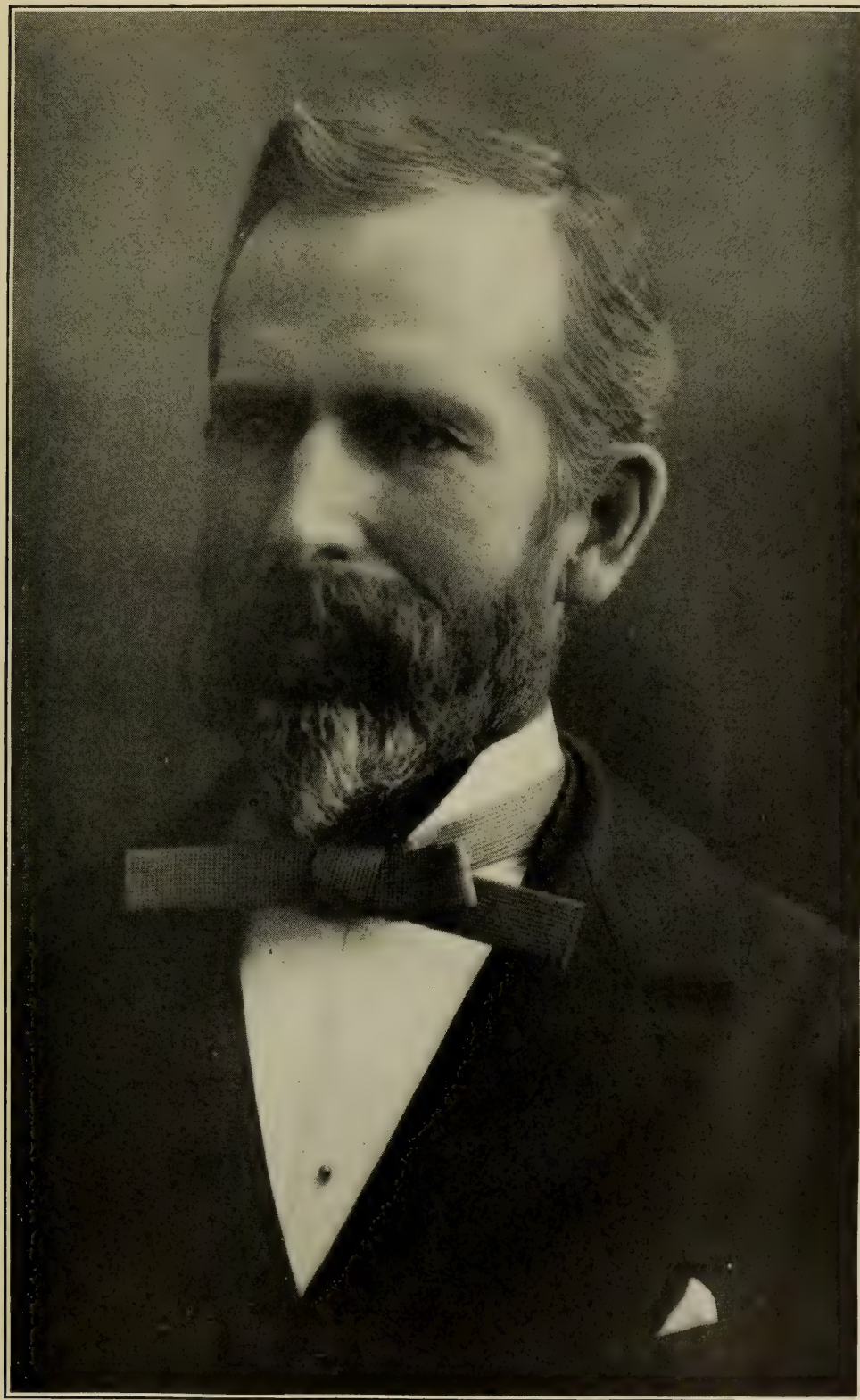
MEMORIAL OF JAMES E. TODD¹

BY FRANK LEVERETT

James Edward Todd, one of the charter members of our Society, was born at Clarksfield, Ohio, February 11, 1846. His father, Reverend John Todd, a Congregational minister, took up pioneer work in southwestern Iowa in 1850, and it was in these pioneer surroundings that the subject of our sketch grew up. The nearest store was 20 miles away, and the grist-mill still farther. Hulled corn was long the main diet in his childhood. Economy and industry were made imperative and habits of ease or indolence were not permitted. His father was one of the founders of Tabor College, at Tabor, Iowa, and it was there that young Todd received his early education. From there he went to Oberlin College, where he graduated in 1867. He then attended Union Theological Seminary in New York, in 1867 to 1869, and returned to Oberlin to obtain the degree

⁴³ Op. cit.

¹ Manuscript received by the Secretary of the Society February 2, 1923.



J. E. Todd

of Bachelor of Divinity in 1870. During the Civil War he served 100 days in 1864 as private in Company K, 150th Ohio Infantry. He was married June 15, 1876, to Miss Lillie Carpenter, of Tabor, Iowa, and is survived by his widow and three sons. The eldest son, Prof. M. E. Todd, is an electrical engineer on the faculty of the University of Minnesota. The second son, E. A. Todd, is a chemist employed in oil plants in Oklahoma. The third son, J. E. Todd, is treasurer of Robert College, Constantinople, Turkey.

Although trained for the ministry, Professor Todd devoted his entire life to the teaching and investigation of scientific matters. He used his influence in reconciling science and religion, and by his earnest Christian life, together with his devotion to scientific truth, did much to illustrate the close relation that science and religion have to the true purpose of life.

For 21 years, from 1871 to 1892, Professor Todd filled the chair of natural science at Tabor College. In the summer months, beginning in 1881, he was employed as a special assistant and later as assistant geologist on the United States Geological Survey. His field of work was chiefly in the Dakotas, in the studies of the glacial deposits. In 1891 he was employed in the summer months by the Missouri Geological Survey in a study of the Quaternary deposits, and in the summers of the next two seasons he had an assignment on the Minnesota Geological Survey, to study the drift deposits and lake beaches in the northwestern part of that State. In 1893 Professor Todd received appointment as State Geologist of South Dakota and as professor of geology and mineralogy in the University of South Dakota, at Vermilion, South Dakota. These positions were held for ten years, during part of which time he was also acting president of the university. From 1902 to 1907 Professor Todd made detailed studies of several quadrangles in South Dakota for the United States Geological Survey, which were the basis for geologic folios published later. In 1907 he was appointed to the chair of geology at the University of Kansas, and in this position he extended his study of the glacial deposits over the glaciated portion of Kansas. This position was held until 1918, when he was retired with the title of professor emeritus of the university. After his retirement poor health prevented further active field-work, but he kept up an active interest in scientific problems to the time of his death, which took place at Lawrence, Kansas, on October 29, 1922.

Professor Todd was skillful in drawing and in the use of the camera in the field, as will appear by reference to the illustrations accompanying his reports and scientific papers. He was accurate to a nicety, and re-

fused to make loose generalizations or take matters for granted. In many cases he withheld his acceptance of the results of his fellow-glacialists until he had himself investigated the phenomena. He was especially guarded in giving his sanction to the current view that there have been several stages of glaciation, separated by long interglacial stages. This finds expression in his writings by the use of the words "so-called Kansan, so-called Iowan," etcetera. The opportunity for detailed study of one of the old drifts in Kansas, however, removed this uncertainty; so that in his later years the Kansan was recognized as a distinctly older drift than the Wisconsin drift, which had been his especial field of study before. While his studies and writings were primarily scientific and educational, he showed a determined purpose to bring out practical results and applications of geology to the needs of the commonwealths he served. This is shown especially in his papers on the building stones, the water supplies, and in the several geologic folios. While Professor Todd's main field of labor was in the Dakotas, his report on the Quaternary of Missouri and an unpublished report on the Quaternary of northeastern Kansas represent a fuller study of these districts than has been made by any other geologist. His contributions to Iowa, Nebraska, and Minnesota geology are also important.

For 40 years Professor Todd was actively engaged in teaching, and his field investigations and writings represent merely what was done by him outside his main occupation. He brought to the class-room the spirit of investigation and of untiring zeal in the development of scientific knowledge, and was held in high esteem by students as well as by his coworkers and fellow-citizens.

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NOTE.—Since the above bibliography was sent to the printer, Dr. C. R. Keyes has published a bibliography of Professor Todd's geological publications in the February, 1923, number of the *Pan-American Geologist*, which contains a list of some of the earliest papers by Professor Todd, that appeared as brief abstracts in the earliest publication of the Iowa Academy of Sciences. It was issued in 1880, but includes papers presented at meetings of the Academy from 1875 to 1880. The abstracts are found on pages 14-21 of this publication, and embrace the following titles:

Remains of elephant found near Glenwood, Iowa. *Proceedings of the Iowa Academy of Sciences*, 1875-1880; 1880, page 14.

- Recent wind action upon loess. *Proceedings of the Iowa Academy of Sciences*, 1875-1880; 1880, page 21.
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- Volcanic ash bed near Omaha. *American Geologist*, volume 15, 1895, page 130.
- Glacial diversion of Missouri River. *Pan-American Geologist*, volume 39, 1923. (In press.)

Doctor Keyes also states that Professor Todd submitted a paper to him for publication in the *Pan-American Geologist*, only a few weeks before his death, on the subject "Glacial diversion of the Missouri River" that will appear in an early number of that periodical.

MEMORIAL OF LEVI HOLBROOK ¹

BY JAMES F. KEMP

The death of Levi Holbrook at his summer home, Center Harbor, New Hampshire, July 26, 1922, diminished by one the already small number of surviving "Original Fellows" of the Society. Starting with ninety-eight in 1889, the group is now twenty-nine. Mr. Holbrook had reached the advanced age of eighty-six years, and, with snow-white hair and beard, had long been one of the striking figures at the meetings of the American Institute of Mining Engineers and those of the American Geographical Society.

Levi Holbrook was born in Marlboro, Massachusetts, March 7, 1836, and was the son of Levi and Eliza (Grant) Holbrook. He traced his ancestry to John Holebrook, of Weymouth, Massachusetts, a prominent figure in the early colonial days. Levi Holbrook fitted for college at the Williston Seminary, East Hampton, Massachusetts, graduating in 1852. A year later he entered Yale and was valedictorian of the Class of '57 and member of Phi Beta Kappa. Some trouble with his eyes called for medical care in Boston for the next six months and led to a horseback journey across the Rocky Mountains to the Columbia River and back. At this time literary ambitions governed Mr. Holbrook and led him to study modern literature and languages at Cambridge, Massachusetts.

¹ Manuscript received by the Secretary of the Society February 10, 1923.

from 1860-63. He was finally compelled to give over these ambitions and entered business life in Boston, moving in 1871 to New York, where he made his home the rest of his life. He employed himself but part time in business and reserved for various scientific and learned societies his leisure and his energies. He was president for a time of the Phi Beta Kappa alumni, resident in New York; was councilor and secretary of the American Geographical Society, and became one of the Original Fellows of the Geological Society of America, among whose organizing committee of five Charles H. Hitchcock was his old classmate at the Williston Seminary and his lifelong friend.

Mr. Holbrook joined the American Institute of Mining Engineers in 1878 and was one of its managers from 1895-97. The famous secretary of the Institute for many creative years, the late Rossiter W. Raymond, was one of his intimates, and in the Institute and the Century Society the writer came to be numbered among his good friends nearly twenty-five years ago. Mr. Holbrook took a warm interest in patriotic societies. He was a member of the Society of Colonial Wars and of the Sons of the Revolution. For some time he served as registrar-general of the Order of Founders and Patriots of America. He was also a member of the New England Genealogical and Historical Society and of the American Fine Arts Society. Mr. Holbrook thus never followed geology as a profession, but was deeply interested in its progress and a warm supporter of its interests. He was a lover of the world of nature and turned often to travel and enjoyment amid mountains and inspiring scenery.

Mr. Holbrook was married December 27, 1871, to Viola Vowers, and he and Mrs. Holbrook had the rare experience of celebrating their fiftieth wedding anniversary in 1921. Mrs. Holbrook followed her husband a few weeks after his death. A son, Clark Holbrook, of Red Bank, New Jersey, and a daughter, Helen, now Mrs. Julian P. Smith, of Upper Montclair, New Jersey, survive their parents.

ADDRESS OF THE RETIRING PRESIDENT

The address of the retiring President, Charles Schuchert, on "Sites and nature of the North American geosynclines," was then presented. Since this paper is a part of the "Symposium on the structure and history of mountains and the causes of their development," it has been held for publication with that series of papers.

With this paper, and after a few announcements of changes in program and directions for local guidance were made by the Secretary, the morning session of the Society ended.

SESSION OF THURSDAY AFTERNOON

The afternoon session was opened at 2.15 o'clock, with President Schuchert in the chair. The object of the symposium announced for this session was briefly reviewed by the chairman, who called attention to the fact that the presidential address given in the morning session is properly a part of this "Symposium on the structure and history of mountains and the causes of their development."

TITLES OF PAPERS PRESENTED

SYMPOSIUM ON THE STRUCTURE AND HISTORY OF MOUNTAINS AND THE
CAUSES OF THEIR DEVELOPMENT*SITES AND NATURE OF THE NORTH AMERICAN GEOSYNCLINES*

PRESIDENTIAL ADDRESS BY CHARLES SCHUCHERT

*THE THEORY OF MOUNTAIN STRUCTURE RECENTLY SET FORTH BY
PROFESSOR KOBER OF VIENNA*BY CHESTER R. LONGWELL¹

Presented in full extemporaneously.

ASIATIC ARCS

BY WILLIAM H. HOBBS

Presented in full extemporaneously.

THE APPALACHIANS

BY ARTHUR KEITH

Presented in full from notes.

EASTERN APPALACHIANS IN THE LATITUDE OF SOUTHERN NEW ENGLAND

BY J. B. WOODWORTH

Read by title.

COAST RANGES AND SIERRA NEVADAS

BY BAILEY WILLIS

Presented in full extemporaneously.

ROCKY MOUNTAINS OF IDAHO AND MONTANA

BY G. R. MANSFIELD

Presented in full from notes.

¹ Introduced by Charles Schuchert.

Read in full.

The papers comprising the symposium as listed above, including the discussions, together with the presidential address of the retiring President, Charles Schuchert, will be printed in full in a subsequent number of the Bulletin.

The session adjourned at 4.50 o'clock.

SESSION OF THURSDAY EVENING

DIVISION OF GEOLOGY AND GEOGRAPHY, NATIONAL RESEARCH COUNCIL

A round-table discussion of "The functions of the Division of Geology and Geography, National Research Council," was held under the chairmanship of Nevin M. Fenneman, at 7.30 p. m., in the University of Michigan Union.

For the purpose of introducing this discussion the chairman had published in *Science*, December 1, a nine-column article setting forth the nature of the organization of the Research Council and of the procedure in the Division of Geology and Geography. The discussion on the contents of this paper and the general work of the division was opened by David White, followed by T. W. Vaughan, John M. Clarke, Alfred C. Lane, W. H. Hobbs, A. C. Lawson, and others.

Speakers pointed out the opportunities for suitable activity by the division and, to some extent, recounted its successful achievements. The import of the discussion was that the Research Council is not an operating concern equipped for and engaged in the conduct of researches, but rather a mode of coordinated effort of the geologists of the United States. For this purpose it affords conveniences, including chairman and office force. It was pointed out that the effect of providing such facilities is not very different from that which would result from the support of a chairman and office at the disposal of active committees of the Geological Society of America. Twenty-two of the twenty-six members of the division are Fellows of the Society.

THE SMOKER

At 8.30 p. m. a smoker was given by the University of Michigan to the Fellows of the Geological Society of America, the Paleontological

Society, the Mineralogical Society of America, the Society of Economic Geologists, the Association of American Geographers, and their friends. This was largely attended and was held in the University of Michigan Union, occupying the entire evening.

SESSION OF FRIDAY MORNING, DECEMBER 29

The morning session was opened at 10 o'clock by President Schuchert, and the report of the Auditing Committee was called for. The following report was read by H. B. Kummel, chairman of the committee:

REPORT OF THE AUDITING COMMITTEE

DECEMBER 28, 1922.

To the Council and Members, Geological Society of America:

The committee appointed to audit the Treasurer's accounts reports as follows:

(1) It has verified the statement as to cash on hand by comparison with the bank statements.

(2) It has checked the receipts from fellowship fees, income from investments, and miscellaneous items and found them correct.

(3) It has not been possible to verify the items listed under Secretary's receipts because of the nature of the items.

(4) It has found that all income due on investments during the year has been paid.

(5) It has compared vouchers for disbursements with canceled checks and with printed statement of disbursements and found them correct.

(6) The securities in the hands of the Treasurer will be checked in Baltimore by Dr. Reid, of the committee, and report made to the Secretary.

(7) The committee takes pleasure in testifying to the excellent way in which the accounts are kept.

HENRY B. KUMMEL, *Chairman*.

ROLLIN T. CHAMBERLIN.

This report was received and accepted, conditioned on receipt of additional report covering the securities.

Harry Fielding Reid, the third member of the committee, was delegated to make an examination of the securities of the Society and submit a written report directly to the Secretary, to complete the committee's duties.

REPORT ON SECURITIES

BY HARRY FIELDING REID

List of Securities

- 2 Texas and Pacific Railway Company first mortgage 5's, numbers 11915, 20892.
- 2 Fairmont and Clarksburg Traction Company first mortgage 5's, numbers 29, 30.
- 3 Chicago Railways Company first mortgage 5's, numbers 20750, 20751, 45871.
- 2 Southern Bell Telephone Company first mortgage 5's, numbers M13217, M13218.
- 2 Consolidation Coal Company first and refunding mortgage 40-year sinking fund 5's, numbers 11850, 11851.
- 3 United States Steel Corporation sinking fund gold coupon 5's, numbers 2964, 2974, 2975.
- 2 American Agricultural Chemical Company first mortgage 5's, numbers 5834, 6356.
- 1 Florida Central and Peninsula Est. 6's, number 2978.
- 1 Louisville and Nashville Railroad Company 10-year 7 per cent note, number M3941.
- 1 Bell Telephone Company of Pennsylvania 25-year first and refunding 7 per cent, number M12813.
- 1 Braden Copper Mines, number 4391.
- 1 Edison Commonwealth Company, number 49652.
- 10 shares Iowa Apartment House stock.
- 40 shares Ontario Apartment House stock.

I certify that the securities in the above list are in the possession of the Treasurer of the Geological Society of America, Dr. Edward B. Mathews.

HARRY FIELDING REID.

BALTIMORE, *February* 10, 1923.

The report of the Council, which had been laid on the table pending the findings of the Auditing Committee, was then taken up and approved.

There being no further business at this time beyond announcements of the Secretary with regard to the handling of transportation certificates, the group photograph, and disposition of the sectional meetings and the meetings of affiliated societies, the scientific program was taken up.

TITLES AND ABSTRACTS OF PAPERS AND DISCUSSIONS THEREON, PRESENTED
BEFORE THE MORNING SESSION

*RECENT WORK IN FRANCE AND SWITZERLAND ON THE STRUCTURE OF
THE ALPS*

BY EMMANUEL DE MARGERIE

Presented in abstract from notes.

A LAYMAN'S VIEW OF THE THEORY OF ISOSTASY

BY C. K. LEITH

(Abstract)

An attempt to discriminate the known facts of isostasy from the various assumptions which have entered into the theory as now known, and a discussion of some of these assumptions from the standpoint of structural geology.

Read from manuscript.

DISCUSSION

Mr. D. F. HIGGINS: Geologists should not confuse the terms "stress" and "strain." In the engineering (physical) sense, stress is a force, strain is a change of shape. To avoid the ambiguity in the word strain, it is better to avoid it altogether and use the word deformation in its stead.

As far as the Rocky Mountain Front Range of Colorado is concerned, Professor Leith's statement that the hearts of the great ranges are granitic does not hold. The Front Range is essentially sedimentary (Precambrian), into which have been intruded the relatively small granite batholiths of Long's Peak to Pike's Peak, for example.

The assumption of a primordial earth of uniform (initial) density is not in accord with the postulates of the Planetesimal Hypothesis. The Fellows of this Society know how the differences of density, established by competent geodetic observations, may be invoked at present to bring about, in part at least, the changes of elevation necessary for the erosional cycle, and hence how they may have started the isostatic-erosional cycle at first. The postulation of an earth of initial uniform density, subject only to stresses due to contraction on loss of heat, would not lead to any but very slight deformation due to the fact of isostatic adjustment.

Mr. T. P. SHEPARD: Professor Leith's statement that the mountain ranges are lightened by katamorphism is opposed by the fact that the light katamorphic material from the mountain ranges is removed by erosion and redeposited on the bordering plains, leaving denser material on the mountains and less dense on the plains.

Remarks were made also by Mr. William Bowie.

RECTILINEAR SHORELINES OF THE NEW ENGLAND-ACADIAN REGION

BY DOUGLAS W. JOHNSON

(Abstract)

Many rectilinear shorelines bordering parts of New England and Acadia have been attributed to faulting. The paper discusses a variety of ways in which rectilinear shorelines are produced, and shows that many such coastal lineaments in the region in question, attributed to faulting, are better explained as the result of other processes.

Read by title in absence of author.

DYNAMICS OF FAULTING AND FOLDING

BY BAILEY WILLIS

(Abstract)

The direction of forces producing faults is considered and it is shown that faults with a high dip require the action of vertical forces in combination with horizontal forces. When we consider the influence of pressure on the strength of rocks we find that horizontal pressure alone will always produce a fault of dip less than 45 degrees.

The forces producing folds are examined, and it is shown that the distribution of folds in the Appalachian region could not have been caused by simple compression, but that forces acting tangentially on the under side of the folded region must have existed. This idea is applied to the elucidation of the results obtained by experiments in folding. An explanation of the nappes of the Alps is suggested.

Read by title.

CRITERIA FOR THE RECOGNITION OF ACTIVE FAULTS

BY STEPHEN TABER

Read by title.

FAULT MAP OF CALIFORNIA

BY BAILEY WILLIS

(Abstract)

Fault map of California; description and exhibition of a map of the State, which shows the principal faults at present known. This map has been compiled from all available data by the Carnegie Institution of Washington, represented by Mr. H. O. Wood, the United States Geological Survey, the University of California, Stanford University, and the Seismological Society of America, working in cooperation, as a contribution to seismology of the State. Active faults—that is, those on which earthquakes are liable to occur—are distinguished from dead faults. The base is the relief map of the State, drawn by J. H. Renshaw, of the United States Geological Survey, which brings out strikingly the relation of the ranges to the active faulting.

FAULTS OF THE COAST RANGES OF CALIFORNIA

BY BAILEY WILLIS

(Abstract)

Faults of the Coast Ranges of California; description of the various types of faults recognized in the ranges: upthrusts, overthrusts, progressive thrusting, regressive thrusting, transverse thrusts, and normal faults; vertical movements of fault blocks involving rotation, protrusion, and depression; horizontal movements; relation of thrusting to folding; antiquity and actual activity of forces; persistence of the structural type; magnitude of the structure; their

relation to the sub-Pacific mass; their interpretation as effects of persistent suboceanic spread.

These two papers by Bailey Willis were presented together extemporaneously.

DISCUSSION

Dr. GEORGE H. ASHLEY: As a result of detailed studies in 1906, 18 terraces were traced on San Pedro Hill, and terraces followed around the ends of the hill, so as to leave no doubt of their terrace character. Again, near San Francisco, on the east side of the San Andrews fault, is a raised block, raised on the west, the Pleistocene deposit sloping to the east from 700 feet above the sea at the fault and passing below the bay on the east.

Remarks were also made by Messrs. A. C. Lawson and R. T. Hill, with reply by the author.

Author's reply to Prof. A. C. Lawson: The terraces north of Santa Cruz are correctly described by Professor Lawson as being level, so far as the two lower terraces are concerned. They have been worked over by the sea and exhibit the effects of wave erosion and deposition. The higher terraces are much less well marked, are discontinuous and eroded. I would not like to say categorically that they are or are not level, since individual judgment must enter into the identification of various benches as more or less surely belonging to the same terrace. I agree with Dr. Ashley that the terraces on San Pedro Hill are marine. They are some 400 miles from Santa Cruz.

LATE TERTIARY AND QUATERNARY DIASTROPHISM IN SOUTHERN CEBU, PHILIPPINE ISLANDS

BY GEORGE D. LOUDERBACK AND R. R. MORSE

(Abstract)

The late Tertiary rocks are markedly deformed by faulting, with the production of hoist and graben forms. Geologic sections will be shown illustrating the character of the faulting and its variation along the strike. The recent diastrophic history is outlined and its effects in the production of faultscarps and marine terraces described. Faulting is believed to be an important process in the production of the island.

Presented extemporaneously.

PARALLEL FOLDS AND BOUDINAGE

BY TERENCE T. QUIRKE

(Abstract)

Parallel folds die out, both upward and downward, by interference of neighboring folds and by the approach of curvature to a straight line. Theoretically, they would die out at infinity, but the folding is almost nothing at a dis-

tance equal to 20 times the diameter of the perfect central fold. Parallel folds represent great shortening along the central axis, which dies out to nothing above and below that axis. It represents a rotational strain with maximum displacement along a plane. The inverse of this fold would be represented by zero shortening along the central plane, increasing to a maximum shortening in both directions from that plane. In this case the folds would not die out from the central axis, but they would increase with distance from the axis. These features are extremely rare, but are represented by the so-called boudinage of southeastern Belgium. The origin of rotational strains which are competent to make boudinage is obscure. Certainly it has no connection with normal folding. It is suggested that it represents a hitherto unrecognized type of major structure caused by longitudinal compression relieved by central bulging.

Presented from notes.

With this paper the morning session closed at 12.40 o'clock.

GROUP PHOTOGRAPH

At the close of the morning sessions those of the members in attendance who could be assembled on the steps of one of the university buildings had a group photograph taken.

LUNCHEON GIVEN BY THE UNIVERSITY

At 1 o'clock members of the Society, together with those of affiliated and associated organizations, were entertained at luncheon by the university in the Michigan Union.

SESSIONS OF FRIDAY AFTERNOON

Two sectional meetings, to be held simultaneously, were organized for Friday afternoon. The papers of Group A—dynamical, structural, glacial, and physiographic subjects—were presided over by Vice-President Washington as chairman, and Vice-President Robert T. Hill was chairman of the section in which the papers of Group B, on stratigraphic, paleontologic, areal, and cartographic subjects, were presented.

There was also a joint session with the Society of Economic Geologists for the discussion of the ore deposits of the copper-bearing rocks of Michigan.

SECTIONAL MEETING OF FRIDAY AFTERNOON FOR GROUP A

The section for the reading of papers on dynamical, structural, glacial, and physiographic subjects met at about 2.30 o'clock, in the Auditorium.

under the chairmanship of Vice-President Washington and with E. O. Hovey as Secretary.

TITLES AND ABSTRACTS OF PAPERS OF GROUP A AND DISCUSSIONS THEREON

CONTRIBUTION TO THE HYPOTHESIS OF MOUNTAIN FORMATION

BY E. C. ANDREWS

Read by title.

EARTH'S CRUST AND ITS EVOLUTION

BY REGINALD A. DALY

(Abstract)

According to records at deep borings, the mean increase of temperature with depth seems to be less rapid in eastern North America than in western and central Europe. In each continent the rate of temperature increase itself increases with depth, at least to the depth of 2,000 meters. Deeper down the acceleration doubtless falls to zero and changes sign, but it appears already clear that extrapolation from the average surface gradient is not likely to give a temperature too high at a depth of the order of 40 kilometers. At that depth, therefore, a temperature of 1,200° centigrade or more may be expected. At that temperature and corresponding pressure, ordinary rock-matter can not be crystalline.

Angenheister's recent study of seismograms has led him to estimate the thickness of the crust under the Pacific as about 41 kilometers, and that of the crust under the surface of Eurasia as about 28 kilometers.

Thus, from two lines of evidence the conception of a thin, solid crust on a non-crystalline, elastico-viscous substratum seems justified and consonant with the facts of geophysics in general, as well as with a sound cosmogony.

That the density of the sub-Pacific crust is greater than the density of the underlying layer is a necessary consequence; hence an important condition for the instability of the crust in past time.

These conclusions may guide speculation as to the development of the crust in its present form. Based on the general idea in the Taylor-Wegener hypothesis of the horizontal movement of continents, a theory of the continents and ocean-basins will be sketched. This theory includes an explanation of the segregation of the earth's salic material in one hemisphere; the intense deformation of the Precambrian formations; the Postcambrian fragmentation of the primitive continent and the associated mountain-building.

Presented extemporaneously.

DISCUSSION

Prof. W. H. HOBBS: As I have listened to Professor Daly's paper I have thought if he were not such a brilliant geologist what a fine trial lawyer he would be. I have been impressed not with the inadequate attention the Wegener theory has received, but rather with the exaggerated attention that

has been accorded it. It seems to bear a great resemblance to the theory of W. H. Pickering, published a good many years ago in the *Journal of Geology*.

Prof. A. P. COLEMAN: Professor Daly shows a poetic imagination in his theory of the shifting of continents for thousands of miles, crowding the edges into mountain ranges; but if we admit that isostatic equilibrium is nearly perfect, there must have been a corresponding flow of the underlying plastic stratum for the same distance in the opposite direction.

Prof. J. A. UDDEN: I should like to inquire why it is necessary to suppose that there is a glassy zone at certain distance below the crust. To my mind, such a zone is not necessary to permit flowage.

Remarks were made also by Messrs. A. C. Lawson, J. L. Rich, H. M. Ami, and H. S. Washington, with reply by the author.

OROGENIC EXIGENCIES OF A ROTARY EARTH

BY CHARLES KEYES

(Abstract)

Since the hypothesis of isostasy is really a multiple one and resolves itself into no less than four distinct hypotheses, it becomes obligatory to determine, not from simple mathematical figuring but from calculation and observation in the field, the position of the geological directrix. Assumption of sealevel as a basis is obviously illogical and entirely unsupported by observation; but the Rocky Mountains in their repeated waxing and waning point to the position of an isostatic datum at about two miles below sealevel as a possible proper basis for calculation. Isostatic compensation appears to be an orogenic effect and not a cause; and there may be explanations for the same phenomena other than isostasy.

Further experimentation along lines reported several years ago (*Bulletin*, 30-70, 1919) emphasizes the function of retardation of the earth's rotation as a primary cause of orogenic disturbance in the globe's straticulate crust. It does not seem necessary to premise permanency of oceanic basins or of continental plaits.

Read by title.

ISOSTASY AS A RESULT OF EARTH SHRINKAGE

BY FRANCIS PARKER SHEPARD¹

(Abstract)

Opposition to the theory of isostasy is directed primarily against geological interpretations of the theory rather than against the geodetic conclusions. Changing these interpretations of the working of isostasy might make it more compatible with the phenomena of geology. Isostasy could be as effective in keeping the crust balanced with a shrinking interior of the earth as with non-shrinking interior. Mountains due to a shrinking interior would tend to keep

¹ Introduced by T. T. Quirke.

in isostatic adjustment. Peneplains and plateaus can be explained without loss of isostatic equilibrium. Periodic diastrophism is opposed to continuous isostasy, but periodic diastrophism is a theory which is based on incomplete field data. Apparent periodicity may indicate only the natural breaks in the evidence of what might be a complete series of diastrophic movements. Such breaks may be caused by the lack of evidence of the stratigraphic data of earth movements, removal of such evidence by erosion or deposition, and by the occurrence of the deformations within the ocean basins.

Read by title.

FISSILITY OF SHALE: SOME FACTORS CONCERNED IN ITS DEVELOPMENT

BY J. VOLNEY LEWIS

(Abstract)

"Shale" and "shaly"—vague and much-abused terms—are applied even to massive claystone, mudstone, and siltstone, and, with more apparent reason, to rocks of alternate lamination; but this structure is obviously stratification and better designated interlamine (or interfoliate) shale and sandstone, limestone and claystone, etcetera. Few structures are so little understood as the fissility of homogeneous clays and unsorted muds—their splitting into shelly flakes and wedgelike to splintery fragments approximately parallel to the bedding. It is proposed to restrict the terms shale and shaly to such rocks.

Theoretically, fissility may develop from orientation of the particles during deposition; but with abundant colloids and fine clay and the great water content of the fresh deposits probably this rarely happens. It is, perhaps, more probable in the fresh-water deposits, with their smaller proportion of colloids, than in those of marine origin. Typical shaly structure is, perhaps, generally secondary and attributable chiefly to two gravitational processes: (1) Compression (condensation), which eliminates much water, reduces the thickness of strata (even to one-fourth of the original dimensions), flattens particles, and orients flaky and elongate fragments parallel to the bedding. (2) Plastic flow, which turns the longest axes into the direction of movement—down the depositional slope.

Each process is aided by the other and also by tidal oscillations and by vibrations due to waves, earthquakes, and offshore slumping. Flow is doubtless largely dependent on colloids (alumina, silica, kaolin-like substances, ferric hydrate, organic matter) and interstitial water, ceasing as particles attain rigid packing.

Such fissility is metamorphic. In contrast with slaty cleavage, it is parallel to the bedding, since it results, not from tangential stress, but from gravitational adjustments due to loading. Much minutely flaky kaolin, chlorite, and mica in shale probably arises from this mild metamorphism. Perhaps natural gas and petroleum also form under these conditions. Expelled by condensation, they migrate, in the presence of water, up the depositional slope and into coarser facies or the porous and cavernous parts of the old land on which the strata overlap. Vibrations and tidal kneading are also doubtless effective factors in the migration. The hydraulic principle probably operates only in the open spaces of the reservoir rocks.

Experiments have shown that compression and flow produce parallel structures in both soft and hard materials, and the processes enumerated must yield similar results in many homogeneous, fine-grained deposits. The efficacy and mode of operation of some of the factors concerned are, however, but imperfectly known. Critical field observations and rigorous quantitative tests are urgently needed.

Read by title.

DEVELOPMENT OF SHRINKAGE CRACKS IN SEDIMENTS WITHOUT EXPOSURE TO THE ATMOSPHERE

BY W. H. TWENHOFEL

(Abstract)

Experimental work in the laboratory with two types of sedimentary materials has shown that shrinkage or mud-cracks develop in these sediments without their being exposed to the atmosphere. Bentonite and powdered hematite, the latter from Mayville, Wisconsin, were used, the latter in only one experiment. The work with bentonite has been repeated many times and has been sustained by field observations, so that the results appear certain.

Presented extemporaneously.

OBSERVATIONS ON THE RANGE AND DISTRIBUTION OF CERTAIN TYPES OF CANADIAN PLEISTOCENE CONCRETIONS

BY EDWARD M. KINDLE

(Abstract)

The concretions described are from the Quaternary sands and clays of Labrador, the Northwest Territories, and Ontario.

The points discussed include the influence of the nucleus on the shape of concretions and deductions from localized distribution concerning some of the factors in their formation.

Five types of concretions, which are primarily the product of lithologic control, are described from the Ottawa Valley. The stratigraphic range of these several types is indicated.

Nomenclature suitable for discriminating some of these types is suggested.

Presented in full extemporaneously.

DISCUSSION

Prof. T. T. QUIRKE: Certain surficial features on marlekor look like welts or small raised ridges; they may have been caused by the filling of shrinkage cracks by hardened material, followed by continued shrinkage of the main mass. Other concretion-like masses appear to have been formed by the rolling of mud balls down clay slopes, with the result that they carry upon their surfaces a sort of wrapping of clay layers about the central parts.

Author's reply: Professor Quirke's observations on marlekor have been made in an area somewhat remote from the one in which my own studies were made, and it is possible that some of the specimens referred to by him may have a different genetic history from that of the marlekor of the Ottawa district. I am not prepared to explain just how the fissures in the interior of the marlekor originated, but the clay pebbles which may be seen in abundance along the Ottawa River in late summer certainly show no such features; neither do any of the mud balls which have come under my notice along the Bay of Fundy estuaries possess any features which suggest in any way a comparable origin for the marlekor. The best evidence, perhaps, that the marlekor were produced by the same general agencies which are responsible for the claystones occurring at a lower level in the clays, is found in the fact that, like them, they are confined to that portion of the clays which lies within a few feet of the surface.

BOOM BEACH (ISLE-AU-HAUT, MAINE): A SEA-MILL

BY JOHN M. CLARKE

(Abstract)

A short beach with rocky floor and bounded at each end by rock cliffs, exposed to the full force of the Atlantic, so confines wave action as to prevent lateral dispersion of abrasive effects, with the result that all boulders constituting the beach are ultimately reduced to forms of perfect symmetry.

Presented in full extemporaneously.

DISCUSSION

MR. CHESTER K. WENTWORTH: I was interested in Doctor Clarke's paper because of its bearing on the problem of the production of flat beach cobbles by abrasion. The idea is extant in many text-books that these are produced by the shoving of cobbles to and fro by the waves. The proof or disproof of this view waits for quantitative studies, and I should like to receive suggestions as to suitable localities for such studies. In particular, I wish to ask Doctor Clarke if there are at Boom Beach any facts which indicate a flattening of cobbles and boulders as abrasion proceeds.

MR. CARL O. DUNBAR: While working along the western coast of Newfoundland I was strongly impressed with the fact that the structure of the rock exercises a controlling effect on the shape of the beach pebbles derived from it. In places along this coast there are thin-bedded, sedimentary rocks associated with dikes and flows of basalt, and the contrast in the prevailing shape of the pebbles derived from each of these types of rocks is most striking. The most homogeneous, igneous rock breaks down into fragments of subequal dimensions, which under the attack of the waves become rounded into sub-spherical forms. On the other hand, the banded sedimentaries break up into flattish slabs and chips that ultimately become very oblate spheroids or disks of the shape of a watch, and although they take on the most perfectly rounded symmetry never approach a spheroidal form.

Remarks were also made by Mr. Arthur Keith.

CRYSTALLINE ROCKS OF THE PLAINS

BY CHARLES N. GOULD

Presented in full extemporaneously.

Brief remarks were made by Prof. R. S. Knappen.

PRECAMBRIAN FOLDING IN NORTH AMERICA

BY WILLIAM J. MILLER

Presented in full extemporaneously.

Remarks were made by Messrs. Ruedemann (by letter) and Coleman and by Miss Fuller, with reply by the author.

NOTES ON THE SALT DOMES OF NORTH AMERICA

BY E. DE GOLYER

(Abstract)

A paper describing the occurrence and structure of the salt domes of the Gulf coastal region of the United States and the Tehuantepec region of Mexico, with a discussion of theories of salt dome origin and a comparison with various European salt dome regions.

Read by title.

SOME STRUCTURAL FEATURES OF NORTHERN IDAHO

BY JOSEPH B. UMPLEBY

(Abstract)

The Osburn fault crosses northern Idaho and presents conclusive evidence of a horizontal component of movement measurable in miles. The plane dips about 65 degrees from the horizontal and, incident to movement along it, sympathetic fractures hundreds of feet long have been opened and reopened, as shown by the sequence of mineral deposition in the Cœur d'Alene district. The reverse faults of the area have much less gouge than the normal ones, indicating that they were caused by vertical rather than horizontal stresses. These stresses may have arisen from an underlying molten intrusion—a possibility supported by a detailed study of the ore deposits, which, in part at least, formed before the magma bed completely solidified. As the mineralization is believed to have accompanied the granite intrusion on the one hand and the faulting on the other, it is suggested that the great horizontal displacement along the Osburn fault represents gliding on a molten subsurface zone.

Read in full from manuscript.

*DATA ON THE GEOGRAPHIC NOMENCLATURE OF THE SOUTHERN CALIFORNIA
AND TEXAS REGIONS*

BY ROBERT T. HILL

(Abstract)

Revised classification of the physiographic features of the Texas region, with sketch map.

A revision of previous earlier classifications made by the author, with accompanying sketch.

A nomenclature map of the physiographic features of southern California.

This diagrammatic map is an endeavor to name and outline the physiographic features of southern California. These comprise a large number of units which have not hitherto been satisfactorily presented.

Presented in full extemporaneously.

SECTIONAL MEETING OF FRIDAY AFTERNOON FOR GROUP B

The section for the presentation of papers on stratigraphic, paleontologic, areal, and cartographic papers met, at about 2.45, in Room F 214, with Vice-President Robert T. Hill in the chair and Charles P. Berkey as Secretary.

TITLES AND ABSTRACTS OF PAPERS OF GROUP B AND DISCUSSIONS THEREON

SUCCESSFUL METHOD OF TEACHING HISTORICAL GEOLOGY

BY GEORGE H. CHADWICK

(Abstract)

The writer's success in teaching historical geology by first working backward from the present seems to be based on a sound pedagogical principle, previously employed by him successfully in the teaching of biology. The linkage of this with other factors of method for increase of interest will be briefly described.

Read by title.

*ORDOVICIAN OVERLAP IN THE PIEDMONT OF SOUTHERN PENNSYLVANIA
AND MARYLAND*

BY GEORGE W. STOSE AND ANNA I. JONAS

Read by title in absence of the author.

CHEMUNG STRATIGRAPHY IN WESTERN NEW YORK¹

BY GEORGE H. CHADWICK

(Abstract)

The upper Devonian of western New York consists of several thousand feet of terrigenous strata in which the outstanding terms have been "Genesee," "Portage," "Chemung," and "Catskill." It is now many years, however, since John M. Clarke, H. S. Williams, D. D. Luther, and others began to point out that these familiar subdivisions are not strictly successive units, but local and overlapping (or dovetailing) facies.

Field studies under Dr. Clarke's direction have now shown that the principles enunciated by him are applicable to these strata across the entire State of New York and beyond, into Ohio. The fossiliferous "Chemung" strata prove to occupy progressively higher horizons in passing westward, as do the red "Catskill" beds that overlie them throughout most of this stretch. Likewise the comparatively barren "Portage" strata rise steadily in the scale in a westerly direction, while black shales of "Genesee" type pursue them upward.

The careful tracing of key horizons across the State into Pennsylvania, together with the writer's previous study of the literature for the Ohio equivalents, leads to the correlations in the table herewith presented, in which vertical dark bands indicate the portions of each section usually ascribed to the "Chemung." The units beneath Lake Erie are checked on well borings.² The defense of the upper portion for Ohio and Pennsylvania will be published separately.

Presented in abstract extemporaneously.

Brief remarks were made by Mr. David White and Dr. I. C. White, with reply by the author.

CORRELATION OF THE POTTSVILLE AND LOWER ALLEGHENY FORMATIONS
IN WESTERN PENNSYLVANIABY B. COLEMAN RENICK¹*(Abstract)*

The reports of the Second Pennsylvania Geological Survey covering the region along the Beaver River and its tributaries, in Lawrence, Mercer, and Butler counties, show that the average interval between the Vanport limestone of the Allegheny formation and the Homewood sandstone, the youngest member of the Pottsville formation, is 50 feet. In the Foxburg quadrangle along the Allegheny River the average interval is 120 feet from the Vanport limestone to what is called the Homewood sandstone in that folio.

The geologic section from the base of the Pottsville to the Vanport limestone was studied along the Beaver River between Homewood and Mercer. The same members were then traced along the outcrop up one of the tributaries to

¹ By permission of the Director of the New York State Museum.

² Title in this Bulletin, vol. 33, p. 152.

³ Introduced by G. F. Kay.

SENECAN				CHAUTAUQUAN				BRADFORD ^m				WAVERLYAN			
UNITS	CUYAHOGA VALLEY	ASHTABULA COUNTY	ERIE CO., PENNA.	CHAUTAUQUA COUNTY	CATTARAUGUS COUNTY	ALLEGANY COUNTY	STUEBEN COUNTY	CHEMUNG COUNTY							
Berea	Berea ss	Berea	Corry ss	Corry											
Bedford	Bedford sh.	Bedford													
Cleveland	Cleveland sh.														
Olmsted															
Hayfield		?	Hayfield sh.	?											
Cussewago		Cussewago	Cussewago ss.	Knapp beds	Knapp cgl. ³										
Riceville		Upper Chagrin	Riceville sh.	Conewango form.	? Oswayo sh. ⁴	Oswayo	?	?							
Lenango	Upper Chagrin	Chagrin	Lenango gr.	Panama ggl.	Cattaraugus ⁵ red beds ⁶	Cattaraugus beds	?	?							
Le Boeuf	?		Le Boeuf ss.		Wolf Cr. ggl. ⁷										
Chadakoin "Quarry s."	Lower Chagrin	Lower Chagrin	"Chemung" beds ²	Chadakoin	Chocolate beds ⁹	Chocolate beds and iron ore.	"Catskill" chocolate beds	"Catskill" red beds							
Girard	x		Girard sh.	Volusia sh.	"Quarry ss." ¹⁰										
Cuba	U				Cuba ss. 12	Cuba ss.	?	?							
Northeast	7	x	"Portage" or Northeast sh.	Shumla ss.	Machias										
Shumla	q	?	x	Shumla ss.	Unnamed (ss)	"Chemung," "Rushford" sandstone	Wellsburg sandstone	Wellsburg sandstone							
Westfield	e	?	x	Westfield sh.											
Laona		?	x	Laona ss.											
Gowanda	"Huron shale"	x	x	Gowanda sh.	Gowanda beds	Gowanda	Gowanda	Chemung							
Dunkirk		x	x	Dunkirk sh.	Dunkirk	Canaseraga ss.	Prattsburg sandstones	Cayuta sh.							
Hanover	shale of	x	x	Hanover sh.	Wiscony sh.	Wiscony sh.	Hatch sh.	1st. Tropicid-leptus zone							
Pipe Creek	of	q		Pipe Cr. sh.	Nunda	Nunda ss.	Westhill sh.	Enfield sh.							
Nunda	well	x	x	Angola sh.	Gardeau sh.	Gardeau sh.	Grimes ss.	Ithaca beds							
Gardeau	records	x	x												
Grimes		x	x												
Hatch		?	?												
Rhinestreet				"Rhinestreet" = Attica sh.	Cashagua	Cashagua sh.	Rhinestreet sh.	Sherburne ss.							
Cashagua	[Olentangy]				Middlesex	Middlesex	Middlesex sh.								
Middlesex	?														

the Beaver River as far as the Beaver-Allegheny divide; then down a tributary which enters the Allegheny River near the northwestern corner of the Foxburg quadrangle. The same section was then studied along the Allegheny River from the northwest corner of the Foxburg quadrangle southward to the mouth of Redbank Creek, in the Kittaninny quadrangle.

As a result of this study the writer believes that the upper Connoquenessing and Homewood sandstones of the Beaver River-Pottsville section are equivalent to the Homewood and Clarion sandstones respectively of the Allegheny River section. It appears that the Pottsville formation of the Foxburg folio should be extended to include the Clarion sandstone which is included in the Allegheny formation, and that the top of the Clarion sandstone should be regarded as the upper limit of the Pottsville formation in that region, because it is the equivalent of the Homewood sandstone of the Beaver River section, which is the first conglomerate-bearing member below the Allegheny formation. On the basis of this classification, the Scrubgrass, Clarion, and Brookville coals of the Allegheny formation in the Beaver River valley are equivalent to the Upper Clarion, Lower Clarion, and Craigsville coals respectively of the Foxburg-Clarion folio.

A brief study of the same members between Mayport, near the southeastern corner of the Clarion quadrangle, and Brookville, in Jefferson County, suggested that the Craigsville coal of the Foxburg-Clarion folio is the equivalent of the Brookville coal near Brookville. Detailed mapping of these members between Mayport and Brookville will be necessary, however, before their relations can be established with certainty in that district.

Presented in abstract extemporaneously.

DISCUSSION

DR. GEORGE H. ASHLEY: The problem has a broad bearing because affecting the type locality. It is thought that the difficulty has arisen partly through misinterpretation of the rocks in the Kittaninny region by members of the United States Geological Survey.

Further remarks were made by Mr. David White and Dr. I. C. White, with reply by the author.

STRUCTURAL STUDY OF A PART OF NORTHEAST TEXAS WITH SOME STRATIGRAPHIC SECTIONS

BY F. JULIUS FOHS AND HEATH M. ROBINSON¹

(Abstract)

PART I. STRATIGRAPHY AND STRUCTURE, BY F. JULIUS FOHS

Much new data on the geologic complex of northeast Texas is available from drilling of several hundred wells (two hundred wildcats) and our own study of the surface geology during the past five years. Fragmentary contributions of much value have been made by others, but, based on more complete data, we discuss general relationships and results.

¹ Introduced by Charles Schuchert.

Due to faulting, reliable stratigraphic sections have heretofore been difficult to obtain, but microscopic studies of well samples and studies of the large group of well logs yield much new information on the thickness of the several formations, the areal extent of the Woodbine sand, the development of Taylor chalk beds, and more precise location of contacts of Nacatoch, Midway, and Wilcox.

Pointing out, first, the larger structural relationships, we describe the Mexia Fault Zone, 5 miles wide and 150 miles long, lying 20 to 30 miles east of and parallel to the Balcones Fault Zone. These zones prove similar in character, with three or more normal, parallel faults, arranged en echelon with similar groups of faults lengthwise of the zone, accompanied by folding, always faulted. Cross-faulting is absent. Both zones follow rigid rock outcrops offsetting shale formations on their west. The Mexia zone effects a partial cutting off of ground waters and appearance of connate waters in connection with oil east of its easternmost faults, resulting in development of four oil pools.

A stratigraphic table, together with cross and longitudinal sections, delineate stratigraphic variations; a sketch map shows relationship of major structural features, and a detailed contour map of a segment of the fault zone shows its local character.

PART II. ORIGIN OF STRUCTURE, BY HEATH M. ROBINSON

An analysis of the stresses producing faults as applicable to the structure under consideration is first discussed; next, the character of the stresses producing faults within described area is treated, showing that dominant stresses are vertical. The zone of offset faults suggests a general weak zone. We then discuss relationship between primary and secondary structural features in the tilting of the Gulf Coast area toward the sea, pointing out the genetic relationship between them. The competency of Upper, Lower, and Pre-Cretaceous beds to transmit stresses is discussed. The general conclusion is reached that movement along deep-lying faults operating on underlying competent beds would produce structural features on the surface beds similar to those found within described area.

Read in full from manuscript.

Brief remarks were made by Dr. Sidney Powers and others.

THE LANCE PROBLEM

BY FREEMAN WARD¹

(Abstract)

Evidence from formations in South Dakota. Brief statement of facts on which there is agreement; also of points under controversy. Discussion of contact of Fox Hills and Lance. Attempt to harmonize conflicting paleontologic evidence. Break between Mesozoic and Cenozoic placed at top of Fort Union.

Read by title.

¹ Introduced by H. E. Gregory.

*OBSERVATIONS ON COAL SWAMPS IN NORTHERN WEST VIRGINIA WHERE
PERMIAN CONDITIONS PREVAIL*

BY JOHN L. TILTON

(Abstract)

Observations in northern West Virginia the past two seasons emphasize the idea of extensive swamps, of mushy constituency beneath the surface, surface covering reedlike, the growing surface creeping out into bodies of water generally fresh, where fresh-water limestone is in process of deposition. Low, fernlike plants (*Cycadofilicales*) are crowding out from the shore and distant trees (tree-ferns?) are rising from the low upland. There is no large growth out upon the swamp at a distance from the shore. The large growths (tree-ferns?) are here confined to the margins of the swamps and to higher ground. The unusual view of a carboniferous swamp is thus the one that fits here where Permian conditions prevail, not the view of a carboniferous swamp that is commonly pictured.

Presented in abstract extemporaneously.

*FURTHER CONTRIBUTIONS TO THE KNOWLEDGE OF THE CRETACEOUS OF
TEXAS AND NORTHERN MEXICO*

BY ROBERT T. HILL

(Abstract)

A. IMPORTANT AND NEWLY DISCOVERED CONTACT DISCONFORMITIES AT THE BASE
AND TOP OF THE GULF SERIES, OR UPPER CRETACEOUS, IN NORTH TEXAS

During the past year I have had the pleasure of discovering in north Texas two important and hitherto undiscovered contacts, one each at the base and top of the Gulf series, or Upper Cretaceous (American usage), of the Texas region which had long been suspected to exist, but which, owing to the unconsolidated and concealed character of exposures, have not hitherto been discovered.

One of these contacts records a disconformity between the top of the Comanche series and the base of the Gulf series, and the other, 85 miles directly east, records a similar disconformity between the top of the Gulf series and the base of the Midway formation of the Eocene Tertiary.

The first locality is situated on the north outer bluff of Denton Creek valley, in southern Denton County, about five miles east of Roanoke. It distinctly shows a disconformity between a Buda-like formation of limestone, with characteristic fossils, which here reoccurs in the top of the Grayson marls of the Comanche series and the base of the Woodbine. The molluscan fauna or species of the former is not known to cross into the latter. This contact is usually obscured by slump in north Texas and has hitherto been considered not proven. Its discovery settles the question of the identity of upper terminal beds of the Comanche series of north Texas with the Buda limestone of the Austin section, and demonstrates that the Woodbine formation lies completely above the latter and is not contemporaneous with it, as has been widely published by Böse and others.

The second locality, about two miles northwest of Lone Oak, Hunt County, shows the limestone of the Midway, with characteristic fossils, resting upon the clays of the Navarro beds of the Upper Cretaceous, with characteristic fossils. This is the second actually observed contact between these formations to have been recognized. The other is on the Rio Frio, some four hundred miles away.

Accurate logs of oil prospecting wells show the thickness of the Gulf series between these localities and along this latitude to be 3,100 feet. Stratigraphic, paleontologic, and photographic details are given.

B. STRATIGRAPHIC POSITION OF THE BUDA LIMESTONE OF THE SOUTH TEXAS
SECTIONS AND ITS RELATIONSHIP TO THE NORTH TEXAS SECTION

This paper gives additional proof of the stratigraphic correspondence between the Buda limestones of the Colorado River section of Texas and the Grayson and Main Street formations of north Texas. It likewise asserts that the Buda formation is not synchronous with the Woodbine formation of north Texas, as erroneously asserted by Böse and collaborators, but that the latter lies above the former with a stratigraphic and paleontologic disconformity between them. It likewise clears up a previously existing confusion, whereby the Tamasopa formation of Mexico has hitherto been erroneously correlated with the Woodbine instead of the Comanchean, to which it belongs.

C. CHANGES OF LITHOLOGIC PHASE IN THE COMANCHE SERIES ADJACENT TO THE
RIO GRANDE AND NOTES ON THE RECURRENCE OF DEEPER WATER
LIMESTONE FAUNAS

Shows the persistence of key faunas of the several divisions of the Comanchean Cretaceous in sections between Red River and the Rio Grande of Texas, accompanied by frequent interpolations of Rudistean limestones along the latter.

Presented in abstract extemporaneously.

PALEOZOIC ROCKS FOUND IN DEEP WELLS IN WISCONSIN AND NORTHERN
ILLINOIS

BY F. T. THWAITES¹

(Abstract)

The paper discusses the formations found in deep wells from the lithologic standpoint only. References to published material on the paleontology are given. The formation names given to the subdivisions of the Cambrian by Ulrich are here defined. Brief notes are given on the surface exposures of the formations. All formations from the Devonian down to the Precambrian are discussed, with special emphasis on the water-bearing Cambrian. The methods by which the deeply covered formations were correlated with those exposed in central Wisconsin are explained in detail. Several cross-sections illustrate the paper.

Read by title.

¹ Introduced by W. O. Hotchkiss.

*MERGING OF THE CARLILE SHALE AND TIMPAS LIMESTONE FORMATIONS IN
SOUTHEASTERN COLORADO*

BY H. B. PATTON

Read by title.

*PRESENT STATUS OF THE GEODETIC WORK IN THE UNITED STATES AND ITS
VALUE TO GEOLOGY*

BY WILLIAM BOWIE

(Abstract)

The geodetic work of the United States, now carried on by the United States Coast and Geodetic Survey, is supplemented to a small extent by the Topographic Branch of the United States Geological Survey and by several cities. There are now in the United States, in addition to the coast triangulation, 20,000 miles of arcs of precise triangulation and traverse, furnishing the geographic positions of many thousands of points or stations. Precise leveling was begun in the United States by the War Department in connection with river improvements and control. Later, this work was begun by the Coast and Geodetic Survey to furnish accurate elevations for the reduction to sealevel of measured base lines. There are now 47,000 miles of precise leveling in the United States, furnishing the elevations of 18,500 bench-marks. The triangulation and precise leveling are essential in the preparation of accurate topographic maps, without which geologists carry on their field-work with great difficulty. A modification of the von Sterneck type of pendulum was made in the United States Coast and Geodetic Survey, under the direction of Dr. T. C. Mendenhall, then Superintendent, which has been used to determine the intensity of gravity at 300 stations in the United States. The geologists are interested in the gravity work because the data furnished by the observations have been extensively used to supplement the isostatic investigations based on triangulation and astronomic data.

The geodetic data furnish accurate physical measurements of direction, distance, and force, which are more effective than any other means in throwing light on the constitution of that part of the crust of the earth which is beyond the possibility of direct observations and measurements.

Presented in abstract extemporaneously.

Brief remarks were made by Mr. David White.

*RECONNAISSANCE TRAVERSE FROM MOJAVE ULOJANE, CALIFORNIA, TO
ROCK CREEK, UTAH*

BY HERBERT E. GREGORY

(Abstract)

The work described includes location of fault south of Death Valley; tracing Mesozoic from Spring Valley Mountains to mantle of San Juan; restudy of the Kanab section of Walcott; definitions of the "Marine Jurassic" and Kaibab; and extension of the Supai-Hermit unconformity.

Presented in abstract extemporaneously.

TOPOGRAPHY AND GEOLOGY OF THE OKANOGAN HIGHLANDS AND COLUMBIA
PLATEAU OF WASHINGTON

BY SOLON SHEDD

(Abstract)

A general discussion of the surface features and geology of the eastern part of Washington. The Okanogan Highlands constitute a large area of metamorphic rocks, part of which was probably originally sedimentary and part igneous. The Columbia Plateau, as used in this paper, refers to that part of the great lava field, in the northwestern part of the United States, which lies within the State of Washington. The surface features of parts of this area are very interesting and are a result, partly at least, of the action of the wind.

Read by title.

TERTIARY STRATIGRAPHY IN THE LOWER RIO GRANDE REGION

BY ARTHUR C. TROWBRIDGE

(Abstract)

A reconnaissance map is presented covering about 13,500 square miles in extreme south Texas. Formations are described. A change in the strike from a northeast-southwest direction in Medina County to a north-south direction in Webb County, and to a north by northwest-south by southeast direction in Zapata and Starr counties, explains some previous differences of opinion concerning the ages of beds and faunas along the Rio Grande between Laredo and Rio Grande City. Partly on stratigraphic evidence and partly on the basis of fossil plants identified by Berry, the Carrizo sandstone of Owen is placed in the Wilcox rather than in the Claiborne, and a new formation, the Bigford, is recognized between the Carrizo and the Mount Selman, the lowest Claibornian formation.

Read by title.

The section adjourned at 4.37 p. m.

ANNUAL DINNER

At 7 o'clock p. m. the Society and its visitors and guests, together with members of the Paleontological Society, the Mineralogical Society of America, the Society of Economic Geologists, and the Association of American Geographers, assembled in the Michigan Union for the annual dinner. There was a very large attendance, and the attractive appointments of the place, with its splendid service, made this one of the most successful and enjoyable events of the kind ever experienced by the Society.

President Schuchert presided and in due time, with appropriate remarks, introduced Prof. H. E. Gregory, who served as toastmaster. In-

formality and simplicity of program, coupled with uniform good humor of both speakers and listeners, combined to make the occasion both highly enjoyable and a real recreation in the midst of three days of strenuous scientific meetings.

Responses to the call of the toastmaster were made by Prof. Emmanuel de Margerie, Correspondent of the Society; J. E. Spurr, for the Society of Economic Geologists; E. T. Wherry, for the Mineralogical Society of America; T. Wayland Vaughan, for the Paleontological Society; Walter C. Mendenhall, for the United States Geological Survey; Wilbur A. Nelson, for the Association of State Surveys, and by R. A. Daly, A. C. Lawson, James F. Kemp, W. H. Hobbs, E. O. Hovey, William North Rice, and John M. Clarke.

GREETINGS TO FOREIGN SOCIETIES

By unanimous vote the Secretary was instructed to cable the cordial greetings of the Society to the Geological Society of France, Professor de Margerie being our honored guest, and to write cordial letters of greeting and good wishes to the Geological Society of South Africa, the Geological Society of China, which was organized only last autumn, and to Sir T. Edgeworth David, of Australia.

After the close of the dinner these instructions were carried out.

RESOLUTION OF APPRECIATION OF E. O. HOVEY, RETIRING SECRETARY

This occasion was used also as an opportunity to express appreciation of the faithful and efficient service of Dr. E. O. Hovey, Secretary of the Geological Society of America for sixteen years. Prof. James F. Kemp made the address in presenting a beautiful silver loving cup to Dr. Hovey as a token of the respect and good-will of the members of the Society.

The following resolutions were then read and enthusiastically adopted:

"At the present annual meeting Dr. Edmund Otis Hovey, Secretary of the Society since December, 1906, is, at his own wish, retiring from office. The undersigned committee has been appointed by President Schuchert to prepare an appropriate resolution and present it for action by the Society.

"Dr. Hovey has held for sixteen years the responsible and exacting office of Secretary. During all this time he has shown exceptional devotion and unsparing fidelity in the discharge of the duties of his office. Under his tenure the Society has maintained the high ideals with which it started on its career thirty-four years ago, and has done so in no small degree because of the influence and sound judgment of its Secretary. The publications have also held true to the exalted standards now long established.

"Dr. Hovey has witnessed during his official life, and has shared in carrying through, at least one important change in policy and organization—that relat-

ing to the affiliated societies. The Paleontological Society became the first affiliate, the Mineralogical Society of America the second, and last year the Society of Economic Geologists joined the group. By this wise arrangement excessive and weakening subdivision is avoided, while a large degree of practicable unity is maintained.

"The Geological Society desires to express and record upon its minutes a warm and cordial expression of appreciation of the unselfish service given by its retiring Secretary and to wish him the successful completion of the scientific labors to which he desires to give his entire efforts and attention.

(Signed)

JAMES F. KEMP, *Chairman.*

JOHN M. CLARKE.

R. A. F. PENROSE, JR."

To this Dr. Hovey, in retiring from this long and useful service, responded briefly and with more than a touch of feeling, as he recalled many years of intimate association with the leading men in American geology.

REPLY BY EDMUND OTIS HOVEY

Mr. Toastmaster, Professor Kemp, Fellows of the Geological Society of America and other friends, you have quite overwhelmed me with your feeling introduction, with the splendid resolutions, which give me more credit than I deserve and which will always be preserved with my most treasured archives, and with this beautiful token of your affectionate regard, which will ever remind me of my long term of most enjoyable service as Secretary of the best scientific society in the world. You may rest assured that I shall follow Professor Kemp's injunction to make the vase "say it with flowers" as a memento to my family of the hosts of friends that my relations with the Society have brought me. I am so greatly affected by all this that I cannot express my feelings in words, or reply adequately to the graceful pre-obituary that Professor Kemp has pronounced regarding me. I can only say I thank you all from the bottom of my heart.

During my incumbency as Secretary about one hundred different men have served on the Council, and they have been drawn from all parts of the country—the representative geologists of America. The close association with such men as Van Hise, Calvin, Gilbert, Hague, Davis, Fairchild, E. A. Smith, Becker, Coleman, Clarke, Adams, Cross, I. C. White, Merriam, Kemp, and Schuchert—to name only the presidents in succession—has been of inestimable value to me.

My relations with the efficient treasurers of the Society, the lamented W. B. Clark and his successor, E. B. Mathews, and with the hard-worked editor, Joseph Stanley-Brown, have been even more intimate and have

led to the warmest of friendships. I cannot let this occasion pass without recording my testimony to the serious devotion to the Society shown by the successive councils and the faithfulness with which they have done their labor of love. From time to time indeed some of the Fellows have voiced some criticism of the conservatism of the governing body; but when these objectors have been taken on to the Council, as they have been when practicable, they have observed the wisdom which has prevailed there, have noted the consideration which always has been given to criticisms, and have uniformly agreed with their colleagues in the conduct of the business of the Society and in the maintenance of the high standards of admission to Fellowship.

A brief survey of the principal events and impressions of the past sixteen years and a few statistics may be of interest to you at this time. Of the 112 men who were enrolled as Original Fellows on the first list issued by the Society, 26 had died and 26 had resigned or dropped out by 1906, leaving 60 on the roll then. At the close of 1922 there were only 27 Original Fellows left, 30 having died and three having resigned in the sixteen years. From 1889 to 1905 the Society elected 287 persons to its Fellowship, and from 1906 to 1921, inclusive, added 286 to this number, a total of 573. There are now 439 elected Fellows on the roll, 134 having dropped out through death, resignation, and failure to maintain their dues. One man is counted twice in this summary, he having resigned as an Original Fellow, and later, on his repentance, having been reelected as a Fellow. There have been, up to the present annual meeting, 678 men and six women connected with the Society as Fellows. In 1909 the Society inaugurated a new class of members by electing seven eminent foreign geologists correspondents. In 1910 six men and in 1912 three more were added to this list. In 1914 six nominations to correspondentship were made by the Council, but on account of the beginning of the Great War the names were not presented at the election of that year. In 1921 one correspondent was elected. Six correspondents have died, hence there are now 11 names on the list in this class. The total membership of the Society at the close of 1922 is therefore 474.

The formation of daughter or affiliated societies began in 1909 with the organization of the Paleontological Society, a vigorous offspring which has gained strength with the passing years, but which still loyally remains under the wing of the parent society. In 1920 a second child was born, the Mineralogical Society of America, which has been somewhat more independent in its existence, since it has maintained a separate channel of publication. Close relations with the Geological Society

of America are secured by these societies through exchange of voting representatives on the respective Councils. In 1920 a third society, the Society of Economic Geologists, came into being as one of our affiliates, the affiliation being recognized by an exchange of non-voting delegates between the two Councils. The formation of these branch societies is an important step in the history of geological science in our country, and it should be guided so as not to injure the parent society.

The publication of the Bulletin has kept on its sturdy way under the hand of the same able editor, Joseph Stanley-Brown, who gave it such prestige as to form an excellent appearance under Secretary Fairchild. May he continue long in the editorship! The papers submitted for publication have come first to the Secretary, and all the scientific contributions except the presidential addresses have been sent out to censors selected by or through the Council for consideration as to acceptability for publication by the Society. This handling of the subject-matter of the Bulletin forms no small part of the Secretary's duties, and I wish here to commend the thoroughness and justness with which the numerous censors have performed their anonymous tasks through love for the Society. The censoring of the papers has contributed largely to the high standard of our Bulletin.

The sales of the Bulletin have been an important source of income to the Society. Up to the close of 1906 the sum of \$9,602.34 had been derived from this source, and in the sixteen years which followed (to November, 1922) the sales amounted to \$22,955.21, an average of \$1,434.70 per year. In the year 1906 the receipts from sales were \$736.25, whereas in the year ending November 30, 1922, they were \$2,004.60. In the three weeks of December which have elapsed since the fiscal year closed, two complete sets of the Bulletin have been disposed of, and the total sales have been increased some \$600. In 1908 all the American exchanges were eliminated from our list of distribution and the price of the Bulletin to libraries was placed at \$7.50 per volume. In 1920 a further increase to \$9 per volume was made necessary by the high cost of printing and paper. We now have some 158 regular subscribers to our Bulletin and 58 foreign exchanges. These statements give some intimation of the growth of the purely clerical work connected with the Secretary's office during the past decade and a half.

We have been sailing very close to the financial wind during the past few years by reason of the rise in the costs of publication and clerical assistance, but by the strictest economy on the part of the officers of the Society we have thus far avoided any increase in our annual dues. These

still remain the same as they were at the organization of the Society, when a dollar could buy more than twice as much as it does now.

During the long period now closing I have not missed a meeting of the Society or of the Council, except during the two years of my enforced absence in the Arctic, when my able successor, Prof. C. P. Berkey, stepped into the breach. I was deeply touched by the generous contribution which the Society made to the Crocker Land Expedition to assist in bringing me home. The close and harmonious association with my colleagues during all these years has been most pleasing. This, with the service rendered to our science, is what makes the Secretaryship of the Geological Society of America worth while. It is a real recompense for the hours and hours of labor necessarily devoted to the discharge of the many and sometimes onerous duties connected with the position.

SESSION OF SATURDAY MORNING, DECEMBER 30

The morning session was called to order by President Schuchert, in the auditorium of the Natural Science Building, at 9.50 o'clock.

TITLES AND ABSTRACTS OF PAPERS AND DISCUSSIONS THEREON, PRESENTED BEFORE THE MORNING SESSION

GEOLOGICAL RECONNAISSANCE IN MONGOLIA

BY CHARLES P. BERKEY

(Abstract)

The data covered by this paper were gathered during the past field season, while acting as geologist for the Third Asiatic Expedition of the American Museum of Natural History, New York.

Five months were spent in the deserts and mountain ranges of central Asia. An itinerary of over three thousand miles gave opportunity for widely extended observations. As much attention as possible was given to geologic structure, stratigraphic succession, formational subdivisions, paleontologic content, deformation history, and physiographic development. More definite statements can be made on these questions than were previously available. The account is intended to cover an advance summary of the investigation and its results.

Presented in abstract extemporaneously.

DISCUSSION

Mr. D. F. HIGGINS: Remarkable is the fact of the great thickness of post-Paleozoic sediments in Mongolia. Near Nan-K'ou Pass, northwest of Peking, I have measured about 20,000 feet of later Proterozoic sediments of von Richt-

hofen's "Nan-K'ou Series." One can well wonder at the tremendous sedimentary records on the Asiatic Continent.

PROBLEM OF MILD GEOLOGICAL CLIMATES

BY ELLSWORTH HUNTINGTON

(Abstract)

A mild climate, with relatively slight contrasts from latitude to latitude and season to season, appears to have prevailed throughout most of geological times. The solar cyclonic hypothesis, when combined with the distribution of land and sea, appears to offer an adequate explanation. Recent investigations show that the cyclonic circulation which gives rise to the typical storms of temperature latitudes and the hurricanes of lower latitudes is intimately dependent upon variations in solar activity. Moreover, an analysis of the relationships of different parts of the sun's disk to barometric conditions over the north Atlantic Ocean and to atmospheric electricity shows a relationship which can not apparently be thermal and which seems to be in harmony with an electrical cause. If this is the case, the sun might be as hot as now, and yet cyclonic storms of all kinds might be greatly reduced if the sun's atmosphere were relatively undisturbed. In that case, the earth's mean temperature would rise, as it does now at times of few sunspots when storms diminish in number. The chief reason for this would apparently be that far less warm air would be drawn from low latitudes and pushed aloft in the centers of storm areas. At the same time the strength of the normal planetary and continental circulations would be increased, because they would suffer less interference from storms. If this happened and if the conformation of the land were such that warm currents easily penetrated to high latitudes, there seems to be no good reason why polar regions should not have enjoyed a climate as warm, perhaps, as that of Ireland.

Presented in full extemporaneously.

Brief remarks were made by Messrs. Leverett and Coleman.

FURTHER EXPERIMENTS ON THE FRACTURING OF HOLLOW BRITTLE SPHERES AND THEIR BEARING ON MAJOR DIASTROPHISM

BY WALTER H. BUCHER

(Abstract)

In a paper read at the Chicago meeting of the Geological Society, the writer presented the results of experiments which showed that the pattern of fractures which form when hollow spheres of glass and of paraffin are fractured by the expansion of water freezing in them, is essentially similar to that shown by the Mesozoic geosynclines as reconstructed by Haug. He further showed that it is possible to explain the origin of the major geosynclines on the basis of such subcrustal expansion.

The purpose of this paper is to present the results of experiments made in the Physics Department of the University of Cincinnati by Dr. R. C. Gowdy

and the writer, in which such spheres were subjected to hydrostatic pressure. In the first series of experiments, thin-walled, hollow glass spheres were thus fractured under compression. In the second series, spheres were used which more nearly correspond to the conditions involved in the deformation of the earth's crust.

Finally, an attempt is made to use these experiments as the foundation for a consistent theory of major diastrophism.

Read from notes.

DISCUSSION

Prof. W. H. HOBBS: Any one who has read Professor Bucher's classical study of ripple-marks will attach importance to any other investigations which he makes. I was one of those who offered objection to the claimed applicability of his experiments on frost-expanded glass balls to the problems of coastal deformation. I must offer objection now to the later series of experiments here presented, on the ground that they do not simulate in any close way the probable stress systems involved in coastal deformation.

Brief remarks were also made by Mr. F. P. Shepard, with reply by the author.

SOME STRUCTURAL FEATURES OF THE PLAINS AREA OF ALBERTA CAUSED BY PLEISTOCENE GLACIATION

BY OLIVER B. HOPKINS

Read in abstract from manuscript.

Brief remarks were made by Messrs. Hobbs and Hill.

CORRESPONDENCE BETWEEN THE GONDWANA SYSTEM OF HINDUSTAN AND THE NEWARK SYSTEM OF THE EASTERN UNITED STATES

BY WILLIAM H. HOBBS

(Abstract)

The Gondwana system of Hindustan presents striking parallels with the Newark system of the eastern United States. These correspondences are especially: (1) the coarse, often red, and sometimes markedly feldspathic materials derived from the Precambrian; (2) the unity of the sedimentary series and its slightly tilted attitude; (3) the occurrence as isolated erosional remnants preserved by inset within crystalline rocks and bounded by faults; (4) the elaborate system of intersecting near-vertical faults and the abundance of basic flows and dikes; (5) intercalated coal seams and ganoid fishes as characteristic fossils; (6) the nature of the differences which characterize the several areas of each system among themselves.

The American Newark has been regarded as probably of Jura-Trias age, based upon the fossils found in the northern areas. The Gondwana system has been definitely shown to have areas of lower, middle, and upper Gondwana age, and these range from the Pennsylvanian to the Jurassic. In most physical aspects the lower Gondwana closely resembles the southern Newark areas, as

the middle and upper Gondwana do the more northern. The lower Gondwana has a basal conglomerate of glacial origin (Talchir beds). During the present season a rapid reconnaissance was made of the Wadesboro area of Newark rocks in North Carolina in the hope of discovering either Pennsylvanian fossils or a glacial conglomerate. Faceted pebbles, but without striae, were found at the base. Proceeding northward to examine the Deep River area, it was learned from Prof. Collier Cobb that he had already discovered, but not yet described, excellent Pennsylvanian fossils from that area, thus confirming the anticipated correspondence in age with the lower Gondwana of Hindustan. Geologists more favorably located should make further search for glaciated pebbles in the basal conglomerates of the southern Newark areas.

Presented in full extemporaneously.

DISCUSSION

Prof. E. W. BERRY: It is perhaps unfair for one who has seen only the abstract of this paper to pretend to criticise its conclusions, but the statements in the abstract are certainly open to criticism, and I would like to point out the harm which, in my judgment, the author does to geological science by such unestablished and far-fetched comparisons as that between the Newark rocks of eastern North America and those of the Gondwana system of India.

I venture to assert that the two series have nothing in common except such features as result from their both having been deposited under continental conditions.

That portion of the Newark which is fossiliferous, and this includes the Connecticut, New Jersey, Pennsylvania, Virginia, and North Carolina areas, is not "probably of Jura-Trias age," but is most clearly and conclusively shown by its fishes, reptiles, mammals, and plants to be not older than the Keuper of Europe, nor younger than uppermost Triassic. These fossils are not confined to the northern area of the Newark, although the so-called Ganoid fishes have been described principally from that area. The mammalia, many reptiles, and the best of the plant materials have come from Virginia and North Carolina. Professor Hobbs is mistaken in his statement that the lower Gondwana most resembles the southern Newark area, and that the middle and upper Gondwana most resembles the northern Newark area.

Paleontologically, and by that I mean both paleozoologically and paleobotanically, there is absolutely no age distinction between the northern and southern areas of Newark rocks. All of the extant evidence is in harmony in pointing to a late Triassic age, and this evidence is overwhelmingly strong for the Virginia and North Carolina areas. Professor Hobbs is mistaken in thinking that he has discovered Pennsylvanian fossils in the Triassic of the Deep River area of North Carolina.

With very considerable faunas and floras known from the Newark rocks, and with the well considered opinions as to age based on comparatively recent studies of the Newark fishes by Eastman, of the vertebrates of the North Carolina Triassic by Gilmore, and the mostly unpublished studies of the Triassic plants of the southern area by the writer, it would seem that Professor Hobbs' conclusions are not in accord with our present knowledge of the subject, nor do they, it seems to me, add anything to that knowledge.

MR. C. K. WENTWORTH: While I am indebted to Professor Hobbs for his suggestion as an addition to my collection of hypotheses for the origin of the striated and faceted pebbles which are widespread in the basins of the James and Potomac rivers, I am forced by the facts to take a very skeptical attitude toward his suggestion. These pebbles and boulders were deposited in early Pleistocene time. The evidence is overwhelming that they were striated in early Pleistocene. Great blocks and boulders, as well as blocks of fragile rocks widespread over the coastal plain, point to ice flotation, indicating the activity of ice far beyond that of the present time. The westernmost occurrence of the striated cobbles is at the edge of the Allegheny Plateau, 160 miles west of any known areas of Triassic rocks. Professor Hobbs has suggested the derivation of the striated pebbles of the Pleistocene from an area of Triassic rocks which have since been removed by erosion. The convergence of early Pleistocene grades with the present grades of the Potomac River at a point near the westernmost occurrence of the striated pebbles indicates that post-early Pleistocene erosion is here to be measured in scores rather than hundreds of feet. The total removal since early Pleistocene time of a Triassic remnant capable of yielding the large quantities of striated pebbles found on the coastal plain is unlikely. So far as my familiarity with the Triassic conglomerates of the Potomac basin goes, I know of no pebbles or cobbles in these rocks which in any important way resemble the smoothed, faceted, and striated pebbles under discussion. The derivation suggested seems wholly untenable.

DR. SIDNEY POWERS: I wish to call attention to the fact that the Squantum tillite near Boston compares in age with the glacial beds in India. The Triassic formations in Nova Scotia show no evidence of glaciation.

MR. GEORGE C. MARTIN: I wish to protest against the general acceptance of faceted and striated pebbles as proof of ancient glaciation. Such evidence has been generally accepted for the supposed continental Gondwana glaciation as well as for glaciation during other periods in pre-Pleistocene time, and that the faceted pebbles from the Newark beds afford such evidence appears to be unquestioned by Professor Hobbs. The frequent present-day transportation of glacial pebbles by ordinary river ice and by floating snags and driftwood for long distances from their source in alpine glaciers or in eroded Pleistocene deposits and their coming to rest in the fluvial, lacustrine, or marine deposits that are now forming in non-glaciated regions is sufficient to show that stronger evidence than even abundant glacial pebbles should be required as proof of glaciation in the locality where the pebbles are found, or of a glacial period at the time when the pebbles were deposited in their present position. The presence of glacial pebbles in ancient conglomerates proves only, in my opinion, that mountains have existed throughout nearly all geologic time, and that the processes of precipitation, erosion, and transportation have always been effective.

Moreover, striated and faceted pebbles can be produced without the agency of even local alpine glaciers. The banks of Yukon River from high water at least to low-water mark, in many places, have a natural pavement of cobbles. The grinding of ordinary river ice, with the embedded sand and gravel that it picks up on the banks as it passes down the river each spring, has produced facets, scratches, and polished areas on the upper surfaces of the cobbles of the pavement. That these marks are of non-glacial origin is shown by the fact

that they occur only within the range of the floods, usually only on the upper surfaces of the cobbles, and on cobbles of undoubted local origin in a region that has never been glaciated. If I am not mistaken, I have even seen articles of modern human manufacture that bear such marks. Such cobbles after being faceted on one side are sometimes turned over and acquire other facets. They then bear a very marked resemblance to glacial pebbles and are indistinguishable from the faceted cobbles from the Potomac Valley which Professor Hobbs believes may be derived from glacial Newark conglomerates. I believe that such effects may be produced on the banks of any river that has occasional ice jams. The grinding of the large volume of ice that passed down the Potomac in March, 1918, in my opinion, may have been sufficient to produce such marks, and such ice jams if repeated many times would certainly do so, for the cobbles embedded at the surface of the mud, especially if the mud were frozen, would remain in place and receive repeated scourings.

Facets and striæ can also be made without ice action of any kind. If a conglomerate that is not so strongly cemented that it will break across rather than around the pebbles is sheared, the pebbles will grind against each other and many of them will receive facets and striæ that are indistinguishable from those of glacial origin. Of course, the movements may be so localized that ordinary slickensides will result. But if the conglomerate is but weakly cemented, or if it is in a position approaching the zone of flowage, the movement may be distributed throughout its mass, so that many faceted pebbles may result, or even the whole conglomerate may be so thoroughly ground up that it resembles a tillite. I believe that many supposed "tillites" have this origin. Some of the early Tertiary conglomerates in the Matanuska Valley, Alaska, contain abundant faceted and striated pebbles that apparently are as characteristically of glacial origin as the recent glacial pebbles of the same region, yet these conglomerates are interbedded with rocks that contain warm-climate plants, including even palms. I broke open one of these pebbles, which proved to have been slightly sheared, and found that the "glacial striæ" inside the pebble were just like those on the outside.

Mr. DAVID WHITE: In his parallel between the Atlantic Trias and the divisions of the Indian Gondwana, Doctor Hobbs seems to have given great weight to the points of physical resemblance. The statement as to the paleontology of the Deep River basin appears to constitute corroboration from an outside source. I fear, however, that Doctor Hobbs has given too ready acceptance to a Paleozoic reference of the Deep River beds, which should not be classed as Permian before the fossils are passed on by the appropriate specialist or specialists.

QUANTITATIVE CRITERIA IN PALEOGEOGRAPHY

BY RAYMOND C. MOORE

(Abstract)

Volumetric determinations of geological formations afford information, in certain instances, of paleogeographic significance; but, due to the quantitatively unknown values of various components, definitely detailed conclusions are not ordinarily possible. Concerning assumed distribution of sea and land

at various times, as in the case of supposed continental masses like Gondwanaland, Atlantis, and the intercontinental land-bridges of biogeographers, consideration quantitatively of total land and sea areas is important. Unless wholly unwarranted assumptions as to change in the volume of the seas are made, the depth of oceanic depressions must, in a measure, be related to total marine area. Some published paleogeographic maps indicate world seas so reduced that if the waters were actually restricted to areas designated, the containing depressions would have to be excessively deep.

Presented in abstract from notes.

DISCUSSION

Prof. C. SCHUCHERT: I am pleased to see Professor Moore trying to get at the quantitative values of the marine transgressions. It is a most difficult problem, and all the more so when a good geologist makes of the entire Pacific basin a continent in order to explain more easily the existence of his circumferential geosynclines. That the present continents were larger in geologic time than they are now most geologists admit, but how far they extended beyond the present shorelines is a vexed question. Since the ocean bottoms move as well as the continents, great areas of the latter have been fractured into the oceanic deeps, and active volcanoes and thermal springs are constantly increasing the volume of water, while great quantities of it are being taken up by the lithosphere. These factors make the problem of quantitative oceanic oscillations almost unsolvable. Nevertheless, the problem must be kept in mind, and, as well, that of the theoretic placement of continents where now are oceanic deeps.

Further remarks were made by Mr. Higgins, with reply by the author.

KEWEENAW GEOTHERMAL GRADIENTS AND THE ICE AGE

BY ALFRED C. LANE

(Abstract)

The rate of increase of temperature in the deep copper mines averages about 1 degree Fahrenheit in 105 feet, but is greater in depth, about 1 degree Fahrenheit in 90 feet. While the mean air temperature in Calumet is 39.4 degrees, the mean ground temperature is over 43 degrees, owing to the blanketing effect of snow. The change in gradient is due to a rise in surface temperature from freezing (32 degrees) to 43 degrees about 11,000 years ago.

The deeper gradient is only what might be expected with rocks of this diffusivity, low in pyrite, with no signs of recent exothermal reactions, low in radioactivity.

Exhaustion of heat from below in early times and an exceptionally thick crust, as indicated by isostatic observations, are also to be taken into account.

Presented in abstract from notes.

Brief remarks were made by Messrs. Daly and Van Nostrand, with reply by the author.

VOTES OF THANKS

At the close of this, the last general session of the meeting, most hearty votes of thanks were passed to President Burton and the Board of Regents of the University of Michigan for the generous hospitality extended to the Society in connection with the thirty-fifth annual meeting, and to the local committee, particularly to its chairman, Prof. Walter F. Hunt, for the perfection of the arrangements which had made the Ann Arbor meeting of the Society memorable for comfort and convenience in all of the requirements of a large and complicated program.

SATURDAY AFTERNOON SESSIONS

Two sectional sessions were held simultaneously on Saturday afternoon.

The papers of Group A, of dynamical, structural, glacial, and physiographic nature, were read in the auditorium of the Natural Science Building. President Schuchert opened this session, with E. O. Hovey acting as Secretary.

Papers of Group B, of petrologic, mineralogic, and economic nature, were read in Room G 217, with Vice-President H. S. Washington in the chair and F. E. Wright acting as Secretary.

TITLES AND ABSTRACTS OF PAPERS OF GROUP A AND DISCUSSIONS THEREON

PHYSICAL HISTORY OF THE COLORADO FRONT RANGE

BY F. M. VAN TUYL AND G. W. MACHAMER

(Abstract)

The Front Range represents a great anticlinal uplift locally faulted and everywhere profoundly eroded. The Cretaceous and older sedimentaries which once covered the area have been entirely removed over the crest of the structure, thus exposing the Precambrian crystallines.

The appearance of a large amount of volcanic debris in the Denver and Middle Park beds indicates igneous outbreaks in the range at the time they were deposited. In the present foothills area a few lava flows and dikes were formed at this time. There is evidence that the basaltic flows of North and South Table Mountains at Golden were derived from a volcano on North Table Mountain itself, rather than from a fissure now occupied by a dike several miles to the north.

The appearance of boulder beds in the upper portion of the Denver formation suggests readjustments in the mountains to the westward, possibly preliminary to the great uplift. Subsequent to the deposition of the above-mentioned continental fans there were profound orogenic movements which de-

formed these sediments as well as the older ones. The foothills monocline was developed at this time. The date of the post-Denver orogeny has not been definitely fixed. In the Wet Mountains area, directly south of the Colorado Front Range, R. C. Hills found evidence of pronounced movements succeeding the Eocene Bridger. It is possible that there were two or more Eocene uplifts. Some students of Rocky Mountain geology believe that a peneplain was developed in the Front Range in mid-Tertiary time. In the Cripple Creek district, Lindgren and Ransome report evidence of a prevolcanic plateau upon which the fragmental debris of the Cripple Creek volcano was spread. If a mid-Tertiary peneplain existed, a renewed uplift of the range must have taken place in late Miocene or early Pliocene time. Near the close of the Tertiary this erosion surface was bowed upward. The late Tertiary uplift inaugurated the present cycle of stream erosion. There is evidence that preglacial erosion proceeded much more rapidly in the foothills area than within the higher portion of the range. The present relief features of the foothills undoubtedly resulted very largely from preglacial erosion, since the glacial gravels, as shown by their present relationship, partly buried a topography very similar to the present one.

Read by title in absence of authors.

STRUCTURAL FEATURES OF THE COLORADO PLATEAU AND THEIR ORIGIN

BY RAYMOND C. MOORE

(*Abstract*)

The Colorado Plateau is an elevated region, comprising portions of Utah, Colorado, Arizona, and New Mexico, which is mainly composed of essentially flat-lying sedimentary formations ranging in age from Cambrian to Tertiary. Aside from gentle warping, which has affected all of the region, the stratified rocks of the plateau province are affected in various places by three types of structural deformation: (1) persistent, sharply defined monoclinical folds, (2) localized steep arching in association with laccolithic igneous intrusion, and (3) faults.

The monoclinical folds exhibit an axial trend which is dominantly north-south, and in practically all cases the inclination of the steep limb of the fold is to the east. The dip in this direction averages about 40 degrees, but ranges locally to 70 degrees. From the crest of such a fold the strata are commonly very gently inclined to the west. The structures are therefore very asymmetrical anticlines. The rocks involved in this type of deformation range in age up to the youngest Cretaceous of the region, but do not include any of the Tertiary (Eocene) formations. From the fact that some of these folds, as beneath Aquarius Plateau, in southern Utah, and in the Chuska Mountains of northeastern Arizona, were truncated by erosion before burial by the earliest Tertiary of the region, it appears that the age of the folding is post-Cretaceous and pre-Tertiary.

The deformation associated with the laccolithic intrusions consists of sharp upturning and arching of the strata immediately adjacent to the intrusion. Upper Cretaceous beds are involved in this disturbance, but in no case have

Tertiary deposits been found in areas affected by the laccoliths. Except that the intrusions and accompanying deformation followed most of the Cretaceous, it is not possible definitely to determine the age relations of the movement.

The faults, like the monoclinical flexures, have a predominant north-south trend. They are of the normal type, with the downthrow persistently to the west. The displacements are comparable in size to the monoclines, involving movements with a vertical component ranging from a few hundred to more than two thousand feet. In all cases observed, these faults are more recent than the Tertiary formations of the region, and they belong, therefore, to a different chapter in the history of the province than the monoclines.

Analysis of the monoclinical structures indicates that the displacement involved has been dominantly vertical rather than horizontal, but the presence of horizontal compressive stresses at the time of the deformation is indicated by the occurrence of some lateral movement and by the fact that the adjustment to the stresses was accomplished by folding rather than faulting. On the other hand, the forces which produced the large faults at a subsequent epoch appear to have been of a tensional nature. Instead of being squeezed together, blocks of the plateau tended to pull apart, one slipping downward on another. Both types of deformation are probably a response to isostatic adjustments, but in the one case horizontal compression, in the other tension, appears to modify the structural expression of the vertical stresses. The deformation associated with the laccolithic intrusions is evidently caused by the forces producing the intrusion.

Presented in abstract extemporaneously.

Brief remarks were made by Prof. A. C. Lawson.

STRUCTURE OF THE SPRING MOUNTAIN RANGE, SOUTHERN NEVADA

BY D. F. HEWETT

(*Abstract*)

Spring Mountain is a crescentic range, convex toward the northeast, about 75 miles long, in southern Nevada, west of Las Vegas. The highest point, Charleston Peak, 11,910 feet high, rises nearly 10,000 feet above the nearby valleys. Detailed mapping of the southern third of the range during 1921-22 yields the following conclusions: The section exposed ranges from the lower part of the Upper Cambrian to the Jurassic. The Cambrian, Devonian, Mississippian, and Pennsylvanian sections include about 6,500 feet of dolomite and limestone with traces of shale and sandstone. The Permian, Triassic, and Jurassic sections include 1,000 feet of red and buff sandstone, 400 feet of limestone, 50 feet of red shale, 600 feet of thin-bedded limestone, 1,000 feet of red shaly sandstone, and 2,200 feet of buff sandstone.

In late Cretaceous time (?) the beds were gently folded along axes trending west of north; then three distinct blocks were successively thrust from the southwest. The lowest thrust is the flattest, the dip ranging from 9 degrees to 15 degrees; the higher thrusts are steeper. In each block there are local steep thrusts with small displacement. The thrust faults were closely followed by a group of early normal faults that trend north and dip west. Solutions

bearing lead and zinc sulphides were introduced along the early normal faults, and spread out in the Mississippian and lower Pennsylvanian limestones. When they were introduced the nearby limestones were extensively altered to dolomite. Later (middle Tertiary?) a second system of normal faults of northwest trend and northeast dip broke the early faults and ore bodies. Finally, in late Tertiary time, there were sporadic normal faults of small displacement.

The present range is not limited by normal faults and it is therefore not a fault-block range. The poorly defined scarp that forms the eastern front is due to erosion acting on the relatively soft Jurassic sandstone which underlies the Cambrian dolomite thrust upon it. Potosi Peak (8,504 feet), the highest peak in the southern part of the range, coincides with a large thrust block and is limited northeastward by a late normal fault.

Presented in full extemporaneously.

Brief remarks were made by Messrs. Hill and Lawson, with reply by the author.

*PLEISTOCENE OF NORTHWESTERN ILLINOIS: A GRAPHIC PRESENTATION OF
SOME OF THE CHIEF LINES OF EVIDENCE*

BY MORRIS M. LEIGHTON

(Abstract)

A map of northwestern Illinois will be presented which will show (1) the distribution of the known occurrences of gumbotil, (2) old soils separating the loess and the till, (3) weathered till beneath unweathered loess, and (4) unweathered till beneath unweathered loess. Graphs will also be used to show the depths of leaching found in the different drift areas of northwestern Illinois and also in the Iowan drift area of northeastern Iowa. The direction from which the ice came and the resultant changes in drainage, involving the cutting of the Mississippi River gorge at Cordova, will be dealt with.

Presented in full extemporaneously.

Brief remarks were made by Mr. Leverett, with reply by the author.

*FOSSILIFEROUS LOESS BENEATH TILTED GALENA DOLOMITE AT THE
BORDER OF THE BELVIDERE LOBE, IN NORTHWESTERN ILLINOIS*

BY MORRIS M. LEIGHTON

(Abstract)

During the past field season an exposure in Winnebago County, Illinois, was found which shows tilted Galena dolomite over fossiliferous loess. The fossils of the loess are badly crushed, but four distinct species were found, indicating a considerable fauna. Curator Frank C. Baker, of the University of Illinois Museum, pronounces them of early Peorian aspect. The position of the Galena dolomite is such as to indicate glacial ice-shove. The exposure is situated at the border of the Belvidere lobe, which the author previously referred to the early Wisconsin stage.

Read by title.

LATE TERTIARY AND PLEISTOCENE TERRACE PLAINS OF THE MIDDLE
ATLANTIC COASTAL PLAIN

BY CHESTER K. WENTWORTH ¹

(Abstract)

The terraces and associated formations of the middle Atlantic Coastal Plain and adjacent parts of the Piedmont Plateau are mainly of fluvial and sub-ordinately of marine origin. In the basin of the Potomac River there are six in number, which may practicably be mapped as follows: Tenley, Brandywine, Sunderland, "C" (Wicomico of Shattuck), "B" (Talbot of Shattuck in part), and "A" (Talbot of Shattuck in part). The two earlier are wholly fluvial as far eastward as the present coast; the latter four are fluvial in the western part of their area and marine in the area adjacent to the coast. The present inclination of the terrace plains is to a large extent the original slope of deposition and is due only subordinately to crustal deformation. Fluvial and marine portions of the terraces are separated by rather abrupt changes in inclination, which are not duplicated in the attitudes of higher and older terraces in the vicinity.

The problems of correlation of plains are still far from solution for the whole coastal area, but the distribution of the glacial boulders and of other unique lithologic constituents of certain of the formations in the area studied most in detail promises to be of great value, as broader areas to the north and south are studied with closer attention to physical and lithologic characters than these have received in the past.

The clear identification of the early Pleistocene Sunderland terrace, as distinct from the present river grade to a point well into the Allegheny Plateau, is of great value in separating Pleistocene from probable pre-Pleistocene terrace remnants, and by its comparison with later terraces this study joins with studies in other regions in demonstrating the very great duration of earlier Pleistocene epochs.

Read by title.

GLACIAL DEPOSITS OF MISSOURI AND ADJACENT DISTRICTS

BY FRANK LEVERETT

(Abstract)

The Kansas drift forms a nearly continuous sheet, except where cut away in valleys about to the Missouri River in Missouri and the Kansas River in northeastern Kansas.

South of these streams and also along the Mississippi below Hannibal, Missouri, and between the Mississippi and Illinois rivers in Pike and Calhoun counties, Illinois, there are scattered boulders and smaller erratics extending from 10 to 30 miles or more beyond the definite till sheet. These may represent an earlier glaciation than the Kansan and be reduced on that account to a scanty deposit. The topographic situation is such that no ponding of waters

¹ Introduced by A. C. Trowbridge.

outside the ice-sheet and resultant floating of erratics beyond the ice-border can be postulated. Some of the boulders are found on the highest divides, in situations where no land barrier could have ponded water outside the ice-border. Such is the case with boulders in high uplands south of Clinton, Kansas, and others near Tipton and Jefferson City, Missouri.

Presented in full extemporaneously.

GLACIAL DRAINAGE ON THE COLUMBIA PLATEAU OF WASHINGTON

BY J. HARLEN BRETZ

Presented in full extemporaneously.

Brief remarks were made by Messrs. Leverett, Leighton, and Meinzer, with reply by the author.

GLACIAL LAKE PROBLEMS

BY GEORGE H. CHADWICK

(Abstract)

A discussion of some obscure features in the Laurentian Lake history, such as the probable outlet of Lake Wayne and its relation to Lake Vanuxem, with description of some hitherto unnoticed outlets and levels in New York State, and preliminary correlation charts as a basis for further work.

Presented in full extemporaneously.

Brief remarks were made by Mr. Leverett, with reply by the author.

ICE ACTION ON INLAND LAKES

BY IRVING D. SCOTT ¹

(Abstract)

The shove of ice on the shores of lakes of moderate size has been ascribed to both expansion of the ice during the winter and to wind-blown jams in the spring. The results of a study of the effects of these processes on the inland lakes of Michigan and a consideration of the relative effectiveness of the two processes will be presented in this paper.

Read by title.

BANDED POSTGLACIAL CLAY NEAR NEW YORK CITY

BY CHESTER A. REEDS

(Abstract)

For two weeks during the month of September, 1922, varve clay, similar to that described by De Geer, Lidén, and Antevs in Sweden, Sauramo in Finland, and De Geer and Antevs in America, was studied by the writer in the clay

¹ Introduced by W. H. Hobbs.

pit exposures in the Hackensack Valley at Little Ferry, New Jersey; in glacial Lake Passaic at Mountain View and Morristown, New Jersey, and in the Hudson River valley at Beacon, Dunnings Point, Brockway, and Roseton, New York.

These studies were undertaken with the object of securing material for a museum exhibit on "Climates, Past and Present," and incidentally to see what the possibilities were of applying De Geer's methods of clay geochronology to the postglacial banded clays near New York City.

The varve clay is present in all of the places mentioned above and there is no question but that the De Geer method of geochronology is applicable. Sections were measured and considerable other data secured. The work of Antevs in the Connecticut River valley, "The Recession of the Last Ice-sheet in New England," published by the American Geographical Society, November, 1922, shows what can be done in this direction in this section of the United States.

Read by title.

ORIGIN AND HISTORY OF EXTINCT LAKE CALVIN, IOWA

BY WALTER H. SCHOEWE¹

(*Abstract*)

Lake Calvin is an extinct glacial lake which was formed by the displacement of Mississippi River during the Illinoian stage of glaciation. The advancing glacier in crossing into Iowa blocked the valley of Mississippi River and filled it with ice. This necessitated the finding of a new course to the west. The stream found an opening by way of the Maquoketa River valley and flowed first westward, then to the southward, through Goose Lake channel, to the valley of Wapsipinicon River, and finally, over the low divide between Mud and Elkhorn creeks, to the valley of the Cedar at Moscow; thence, continuing southward to the junction of Iowa and Cedar rivers at Columbus Junction, the combined waters of the Mississippi, Maquoketa, Wapsipinicon, Cedar, and Iowa rivers and those flowing from the edge of the ice, found their pathway obstructed on the one side by the great ice-wall of the Illinoian ice-sheet and on the other by the Kansan bluffs, which stand 120 to 140 feet high. As the waters were unable to find an outlet, they rose and formed a vast and deep expanse of water, to which Udden gave the name "Lake Calvin." During the long existence of the lake the surplus water found its way to the unfilled valley of the Mississippi below Fort Madison by way of an abandoned channel south of Columbus Junction.

Field evidence in the form of lacustrine silts and clays, wave-rounded shorelines, ice-rafted boulders, shingle or beach gravels, associated sandy shore deposits, lake terraces, an inlet and an outlet, and a comparison of the relative widths of the Iowa and Cedar rivers within and without the lake basin—all point to the former existence of Lake Calvin.

Lake Calvin existed to the time of the Iowan ice invasion. The long duration of the lake is in complete harmony with the present-day conception regarding the formation and origin of the gumbotils. It has been demonstrated by Kay that the formation of gumbotil is an exceedingly slow process. The

¹ Introduced by Dr. George F. Kay.

Illinoian gumbotil, which is at least five feet thick, outcrops near the valley walls of the Iowa-Cedar River and along both sides of the Mississippi. Hence these two valleys are incised below the Illinoian upland plain and are post-Illinoian gumbotil in age. Therefore the lake could not have found its discharge by way of them, and the displaced Mississippi must have followed the course south of Columbus Junction until the lake was eventually drained by way of the Iowa-Cedar River valley. The thickness of the deposits in the lake basin, the well wave-rounded shorelines, and the relation of the contact between the lake and the fluvial terrace all point to the same conclusion regarding the long duration of Lake Calvin.

Due to stream piracy of the streams developed on the newly formed Illinoian drift plain after the formation of the gumbotil, Lake Calvin was eventually tapped and drained.

Read by title.

PHYSIOGRAPHY OF THE PARIA RIVER VALLEY, SOUTHERN UTAH

BY RAYMOND C. MOORE

(Abstract)

Paria River is one of the main tributaries of the Colorado in southern Utah, its course trending south-southeast from the border of the high Tertiary plateaus to the head of Marble Canyon at Lees Ferry. The drainage basin of this stream exhibits physiographic relations which are typically representative of a large part of the Colorado Plateau province.

Essential factors in the shaping of land forms in the Paria Valley are the semi-arid climate, the character and structure of the rock formations, elevation with respect to the master stream, and geologically recent changes in elevation. Annual precipitation is small, but the rains are torrential and the proportion of run-off is large. Canyons are a dominant topographic feature. The rocks consist of alternating hard and soft divisions which are in the main inclined to the north. About midway in its course the river crosses obliquely a steep-dipping monoclinal fold, along which are developed prominent hogbacks. A large north-south fault, with upthrow on the east, crosses the upper part of the drainage basin. The hard strata produce escarpments and hogbacks, the soft produce valleys and badlands. A difference in elevation of more than 7,000 feet exists between the headwaters of some of the tributaries and the mouth of the Paria.

Analysis of the physiographic features of this interesting region permits recognition of at least two erosion cycles belonging to late Tertiary and recent geologic history, and, as noted by observers in some other parts of the plateau province, there is indication of displacement by faulting at more than one epoch. The plateau scarp west of the upper Paria Valley, which now has an elevation of more than 2,000 feet above the valley, is on the downthrown side of one of the large faults, the valley itself being in the upthrown block.

Read by title.

*SAND RIVERS OF TEXAS AND CALIFORNIA AND SOME OF THEIR
ACCOMPANYING PHENOMENA*

BY ROBERT T. HILL

(Abstract)

(a) Certain rivers of the Great Plains region, interior deserts, and southern California constitute a class for which the name "sand rivers" is proposed. The Red River of Texas and the Santa Ana River of California are types. These are streams which deposit much of their sand load along their middle courses, to be subsequently removed by wind.

(b) The "windrow" dunes of the Red River of Texas. On the south side of the Big Bend of Red River, in Wichita County, Texas, there are many elongated sand-dunes, occurring over a wide, normally dry, second bottom of the river and parallel to the stream. These are named "windrow dunes," owing to their resemblance to windrows of a hayfield, and they are described as one of the effects of disposition by the wind, after deposition on the sand flats, of the load of sand rivers.

Presented in full extemporaneously.

*SEDIMENTATION AT THE MOUTHS OF THE MISSISSIPPI RIVER—PRELIMINARY REPORT*¹

BY ARTHUR C. TROWERIDGE

(Abstract)

Two months of field-work below New Orleans in 1922 yielded a number of notes pertaining to (1) the flood of 1922, the highest water on record; (2) the relations of turbidity and total load to the maintenance of navigable channels; (3) the gradual closing, by deposition, of some of the mouths of Pass a Loutre without permanently injuring South Pass; (4) the depth of the delta material; (5) the methods and rates of delta growth; (6) the constitution of the deposits on natural levees, in the passes, in the bays, and on the offshore bars; (7) recent enlargement of South Pass in relation to its navigability; (8) the projected opening of Southwest Pass to navigation; (9) various other engineering projects in relation to sedimentation, etcetera.

Read by title.

GEOLOGICAL MAP OF THE BUSHVELD COMPLEX, TRANSVAAL, SOUTH AFRICA

BY CHARLES PALACHE

(Abstract)

Exhibition of the map of the Bushveld Complex prepared by the Geological Survey of the Union of South Africa; explanation of some of the major features of the map; illustrations of structure and scenery of part of the region.

Presented in abstract extemporaneously.

¹ Paper presented by permission of the U. S. district engineer in New Orleans.

TITLES AND ABSTRACTS OF PAPERS OF GROUP C AND DISCUSSIONS THEREON

METAMORPHISM OF QUARTZITES BY THE BUSHVELD IGNEOUS COMPLEX

BY FRED. E. WRIGHT

(Abstract)

In this preliminary paper the results of a field study of the changes produced in quartzites metamorphosed by invading magmas of the Bushveld igneous complex are given. The changes effected by granitic magmas are noticeably different from those produced by noritic magmas. Several series of specimens illustrating these differences, the formation of magmatites with abundant feldspar, on the one hand, the solution and recrystallization of the quartz grains to large individuals one to two inches across without the addition of much extraneous material on the other. The problems offered by these rocks can only be solved by combined field and laboratory study. This problem was selected as of the type suitable for attack by the Geophysical Laboratory, where the development of experimental methods has now reached such a point that certain geological problems can be approached with some assurance of solution.

Presented in abstract extemporaneously.

FUSION OF SEDIMENTARY ROCKS IN DRILL-HOLES

BY BAILEY WILLIS

(Abstract)

The paper discusses the conditions under which the drilling took place.

Read by title.

FUSION OF SEDIMENTARY ROCKS IN DRILL-HOLES

BY N. L. BOWEN AND M. AUROUSSEAU

Presented in abstract extemporaneously.

Brief remarks were made by Dr. Sidney Powers.

XENOLITHS IN THE STONY CREEK, CONNECTICUT, GRANITE

BY JAMES F. KEMP

Presented in abstract extemporaneously.

DISCUSSION

Prof. A. C. LANE: I would like to ask what causes the white halo around the xenolith?

Professor KEMP: One often sees pegmatite structure more marked. In order to bring these out in contrast with stone, we have to sponge them with water. This may have brought about the white halo. I have not seen any development other than the coarser combinations of granite.

*NEW TEACHING DIAGRAM FOR IGNEOUS ROCKS*BY A. B. VAN ESBROECK¹

Read by title.

AEROLITE FROM ROSE CITY, MICHIGAN

BY EDMUND OTIS HOVEY

(Abstract)

A meteorite was seen to fall at 11 o'clock a. m. October 17, 1921, near Rose City, Ogemaw County, Michigan. Its path through the sky was from north-northwest to south-southeast. Three explosions were heard, but only three fragments, weighing together about 10,376 grams, have thus far been recovered. The mass is composed of 17.25 per cent nickel iron and 82.75 per cent mineral matter, principally enstatite and olivine, with some anorthite. The structure is achondritic and agglomeratic. The chief additional feature of interest is the presence of abundant small miarolitic cavities in the mass, which are lined with minute crystals which seem to be of enstatite and olivine. Specific gravity of the finely pulverized material, 3.694.

Presented in abstract extemporaneously.

ORIGIN AND FORMATION OF CERTAIN APPALACHIAN BAUXITE DEPOSITS

BY WILBUR A. NELSON

Read in full from manuscript.

Brief remarks were made by Messrs. Bonine and Lane.

STORMBERG LAVAS OF SOUTH AFRICA

BY FRED. E. WRIGHT

(Abstract)

The Stormberg basaltic lavas of South Africa, like the Deccan traps of India, the Snake River basalts of our Western States and of Patagonia, are of the so-called fissure eruption type and cover vast areas. The Stormberg region has been partly mapped geologically and topographically by Dr. A. L. du Toit. It was the writer's good fortune to spend several weeks last July with Dr. du Toit in a field study of the Stormberg lavas with reference especially to the conditions of their eruption. The lavas are of Jurassic age and form great, nearly horizontal sheets, each flow maintaining throughout about the same characteristics and thickness. The total thickness of the series is approximately a mile; the average thickness of a single flow is about 22 feet. Field evidence indicates that the lavas were highly liquid when they flowed over the land surface, that volcanic gases played a rôle less obviously important than in ordinary eruptions of the central cone type. To solve the problems involved in fissure eruptions, both field and laboratory work are essential if an even

¹ Introduced by James F. Kemp.

approximately quantitative estimate of the importance of the several factors involved is to be made.

Presented in abstract extemporaneously.

DISCUSSION

I. C. WHITE: I found the same series of lavas in a plateau in Brazil of thousands of square miles in extent and exhibiting great massive cliffs. A road that the Brazilians built up the cliffs to the great coal fields and the cattle country cost \$1,000,000. It is simply a mule track cut up the sides of a huge cliff. The dikes from this great outflow penetrated the coal bed, and I traced a finger of dike along the immediate contact with the coal bed for 100 feet and found it had very little metamorphic influence on the coal. It had nearly as much volatile matter as original coal, but only touched the general metamorphic region. The lava was not very hot. The dike was only about 18 inches thick. The same series is found there as occurs in the Gunawanda? country, going over Cambrian? and the underlying Mesozoic beds.

H. S. WASHINGTON: I might add a few words. There are two groups, one containing 48 and 49 per cent of silica, connected by very hard iron, about 14 to 13 per cent. Stormberg basalt contains about 52 per cent of silica and the other about 53½ per cent. They are decidedly low in iron and the most silicious has only 9½ per cent of iron and the other has only 8 per cent.

FRED. E. WRIGHT: One very clearly sees that iron has very little to do with it and usually iron is only one factor that enters into the problem. It is characteristic of all basalt lavas that they came up with very little explosive action. Explosive action occurs chiefly in hydrous magmas. It seems to me that iron with other basalts is one of the important factors; the other is the presence of gases which escaped on account of the high fluidity of the basalts.

L. C. GRATON: I gather from the reference to a colored top that it was somewhat of a different composition than the other composition analyzed. Is that on account of retention of ferric ratio? If the lavas are in the attitude in which they were poured out, was there any slumping? With Dr. Wright's familiarity with Michigan lavas, would he say they are of the plateau type or would their slumping suggest somewhat different mechanism?

FRED. E. WRIGHT: The color of the small flows is red, many times a very intense surface film of bright red. The ordinary lava flow coloration is not so intense. In regard to the slumping, there is a slight tendency toward slumping of several degrees toward the center of the basin which might be due to the weight. It is nearly horizontal. The point I made yesterday was in connection with the Keweenaw flows, where you have flow of uniform thickness and to a great extent almost subaerial and flows off on horizontal basis. It seems to me that Professor Kemp's photographs yesterday were lava flows instead of lava sheets. One was low temperature and stiff, giving out gas, whereas plateau basalts welled out, came to rest, and, being thin, came to rest horizontally.

A HIGH TEMPERATURE VEIN IN MADISON COUNTY, MISSOURI

BY W. A. TARR

(Abstract)

A quartz vein cutting granite occurs in western Madison County, Missouri. The vein contains wolframite, fluorite, and zinnwaldite, indicating its formation at high temperature; and also pyrite, sphalerite, galena, chalcopyrite, and arsenopyrite. Serpentine also occurs in the vein and offers an interesting problem as to its origin.

Read by title.

CRETACEOUS AGE AND EARLY EOCENE UPLIFT OF A PENEPLAIN IN THE SOUTHERN INTERIOR OF BRITISH COLUMBIA AND THE DEVELOPMENT OF THE NORTH THOMPSON RIVER TRENCH

BY W. L. UGLOW

Read by title in absence of author.

*STUDY OF THE IGNEOUS ROCKS OF ITHACA, NEW YORK, AND VICINITY*BY J. H. C. MARTENS¹*(Abstract)*

The dikes of basic igneous rocks in the Ithaca region occur in vertical north-south fissures which parallel the jointing of the Upper Devonian sediments—shales, sandstones, and limestones. They will be called dikes, whether the filling was originally entirely of magmatic origin or, as in some cases, largely composed of sedimentary fragments cemented by a matrix of igneous rock. Metamorphism of the sediments is very slight.

The rock of these dikes is termed Kimberlite on account of the remarkable similarity of the fresher occurrences with the South African material. Both the micaceous and the mica-poor varieties noted in South Africa are represented here. There are also intermediate facies. Striking similarities in minor mineralogical detail, such as anomalous pleochroism in mica, presence of garnet, etcetera, have also been noted. A chemical analysis of material from one of the more micaceous dikes shows close analogy with the mica peridotite of Crittenden County, Kentucky, the alnoite of Mannheim, New York, and some of the South African micaceous Kimberlites.

The significance of such peridotite dikes, occurring at many widely separated localities in the little-folded paleozoic rocks west of the Appalachians, is discussed.

The following papers were read in joint session with the Society of Economic Geologists:

¹ Introduced by A. C. Gill.

*ATTEMPT TO STUDY THE ACTUAL CAPILLARY RELATIONSHIPS OF OIL
AND WATER*

BY CHARLES W. COOK

(Abstract)

The theories concerning the importance of capillarity in causing the accumulation of petroleum have been based largely upon theoretical grounds and to a lesser extent upon experimental evidence. The experiments have been of such a nature that conclusions had to be drawn from what might be called the end results rather than from direct observation of the action. This paper describes the apparatus employed and the results obtained in an attempt to observe the actual relationships of oil and water while in contact and during migration.

Presented in joint session with the Society of Economic Geologists.

*CHEMICAL SUGGESTIONS CONCERNING THE ORIGIN OF LAKE SUPERIOR
COPPER ORES*

BY ROGER C. WELLS

(Abstract)

A number of geologists believe that the copper in the conglomerate and amygdaloid lodes came to its present position in solutions which ascended from depth. The chemical possibilities which would accord with this view and known facts in this region are considered with special reference to the solution of copper and copper compounds by agents which might exist at depth and its deposition by agents which can be assumed to have been present nearer the surface.

Presented in joint session with the Society of Economic Geologists.

SOLVENTS AND PRECIPITANTS IN THE MICHIGAN COPPER LODS

BY ALFRED C. LANE

(Abstract)

The paper discusses in some detail the relative importance of chlorides, carbonates, sulphates, and sulphides in solution, and the precipitation of the copper therefrom by ferrous salts, augite, magnetite, etcetera, or ferric salts, such as hematite and limonite, or hydrocarbons, and trap considered as an alkaline reducing agent.

Presented in joint session with the Society of Economic Geologists.

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FELLOWS

F. J. ALCOCK	WILLIAM H. HOBBS
R. C. ALLEN	OLIVER B. HOPKINS
HENRY M. AMI	W. O. HOTCHKISS
GEORGE H. ASHLEY	EDMUND OTIS HOVEY
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J. AUSTEN BANCROFT	ELLSWORTH HUNTINGTON
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W. S. BAYLEY	G. F. KAY
CHARLES P. BERKEY	ARTHUR KEITH
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E. M. BURWASH	ESPER S. LARSEN, JR.
GILBERT H. CADY	ANDREW C. LAWSON
J. ERNEST CARMAN	W. T. LEE
GEORGE H. CHADWICK	MORRIS M. LEIGHTON
ROLLIN T. CHAMBERLIN	CHARLES K. LEITH
JOHN M. CLARKE	A. G. LEONARD
CHARLES W. COOK	FRANK LEVERETT
R. A. DALY	J. VOLNEY LEWIS
F. W. DE WOLF	WALDEMAR LINDGREN
RICHARD E. DODGE	W. N. LOGAN
CARL O. DUNBAR	F. B. LOOMIS
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ROBERT T. HILL	RAYMOND MOORE

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T. T. QUIRKE	T. WAYLAND VAUGHAN
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JOHN L. RICH	CHESTER W. WASHBURNE
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CHARLES H. RICHARDSON	THOMAS L. WATSON
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FREDERICK W. SARDESON	LEWIS G. WESTGATE
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CHARLES SCHUCHERT	DAVID WHITE
A. E. SEAMAN	I. C. WHITE
R. E. SOMERS	BAILEY WILLIS
J. E. SPURR	FRED. E. WRIGHT

CORRESPONDENT

EMMANUEL DE MARGERIE

FELLOWS-ELECT

VICTOR DOLMAGE

ALEXANDER W. MCCOY

In addition to the foregoing, there were registered at the meeting 117 members of affiliated societies and visitors.

REFERENCE TO CONSTITUTION AND BY-LAWS

The Constitution and By-Laws of the Society were published last year, in volume 33, number 1, pages 162-172. In view of the fact that no changes have been made, it is considered permissible to avoid reprinting in this number. They will be included again in the volume for 1924.

OFFICERS, CORRESPONDENTS, AND FELLOWS OF THE
GEOLOGICAL SOCIETY OF AMERICA

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DAVID WHITE, Washington, D. C.

Vice-Presidents:

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Editor:

J. STANLEY-BROWN, 26 Exchange Place, New York, N. Y.

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L. C. GRATON, Cambridge, Mass.

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(Term expires 1924)

E. S. BASTIN, Chicago, Ill.

L. G. WESTGATE, Delaware, Ohio

(Term expires 1925)

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ALFRED H. BROOKS, Washington, D. C.

*MEMBERSHIP, 1922**CORRESPONDENTS*

- BARROIS, CHARLES, Lille, France. December, 1909.
 BRÖGGER, W. C., Christiania, Norway. December, 1909.
 CAPELLINI, GIOVANNI, Bologna, Italy. December, 1910.
 DE GEER, BARON GERHARD, Stockholm, Sweden. December, 1910.
 DE MARGERIE, EMMANUEL, Strasbourg, Alsace, France. December, 1921.
 GEIKIE, SIR ARCHIBALD, Hasslemere, England. December, 1909.
 HEIM, ALBERT, Zürich, Switzerland. December, 1909.
 KAYSER, EMANUEL, Marburg, Germany. December, 1909.
 KILIAN, W., Grenoble, France. December, 1912.
 TEALL, J. J. H., London, England. December, 1912.
 TIETZE, EMIL, Vienna, Austria. December, 1910.

FELLOWS

* Indicates Original Fellows (see article III of Constitution)

- ABBE, CLEVELAND, JR., College of the City of New York, New York, N. Y.
 August, 1899.
 ADAMS, FRANK DAWSON, McGill University, Montreal, Canada. Dec., 1889.
 ADAMS, GEORGE I., University of Alabama, Tuscaloosa, Ala. December, 1902.
 ADAMS, LEASON H., Geophysical Laboratory, Washington, D. C. Dec., 1922.
 ADKINS, WALTER S., Apartado 150, Tampico, Tamaulipas, Mexico. Dec., 1921.
 ALCOCK, F. J., Geological Survey of Canada, Ottawa, Canada. Dec., 1920.
 ALDEN, WILLIAM C., U. S. Geological Survey, Washington, D. C. Dec., 1909.
 ALDRICH, TRUMAN H., 1026 Glen Iris Ave., Birmingham, Ala. May, 1889.
 ALLAN, JOHN A., Univ. of Alberta, Edmonton, Alberta, Canada. Dec., 1914.
 ALLEN, EUGENE T., Geophysical Laboratory, Washington, D. C. Dec., 1922.
 ALLEN, R. C., 1001 Kirby Building, Cleveland, Ohio. December, 1911.
 ALLING, H. L., University of Rochester, Rochester, N. Y. December, 1920.
 AMI, HENRY M., Victoria Museum, Room 105, Ottawa, Canada. Dec., 1889.
 ANDERSON, FRANK M., State Mining Bureau, 2604 Aetna St., Berkeley, Calif.
 December, 1902.
 ANDERSON, ROBERT V., Menlo Park, Calif. December, 1911.
 ANDREWS, E. C., Geol. Surv. of N. S. W., Sydney, N. S. Wales. Dec., 1920.
 ARNOLD, RALPH, 639 South Spring St., Los Angeles, Calif. December, 1904.
 ASHLEY, GEORGE HALL, State Capitol, Harrisburg, Pa. August, 1895.
 ATWOOD, WALLACE WALTER, Clark University, Worcester, Mass. Dec., 1909.
 BAGG, RUFUS MATHER, JR., 7 Brokaw Place, Appleton, Wis. December, 1896.
 BAIN, H. FOSTER, 1430 33d St. N. W., Washington, D. C. December, 1895.
 BAKER, MANLEY BENSON, School of Mining, Kingston, Ontario. Dec., 1911.
 BALDWIN, S. PRENTISS, 11025 East Boulevard, Cleveland, Ohio. August, 1895.
 BALL, SYDNEY H., 42 Broadway, New York City. December, 1905.
 BANCROFT, JOSEPH A., McGill University, Montreal, Canada. December, 1914.
 BARBOUR, ERWIN HINCKLEY, University of Nebraska, Lincoln, Neb. Dec., 1896.
 BARTON, DONALD C., Amerada Pet. Corp., Houston, Texas. December, 1921.
 BARTON, GEORGE H., Boston Society of Natural History, Boston, Mass. Au-
 gust, 1890.

- BARTSCH, PAUL, U. S. National Museum, Washington, D. C. December, 1917.
- BASCOM, FLORENCE, Bryn Mawr College, Bryn Mawr, Pa. August, 1894.
- BASSLER, RAY SMITH, U. S. National Museum, Washington, D. C. Dec., 1906.
- BASTIN, EDSON S., University of Chicago, Chicago, Ill. December, 1909.
- BATEMAN, ALAN MARA, Yale University, New Haven, Conn. December, 1916.
- BAYLEY, WILLIAM S., University of Illinois, Urbana, Ill. December, 1888.
- BEEDE, JOSHUA W., 200 S. Seneca Ave., Bartlesville, Okla. December, 1902.
- BENSON, W. N., University of Otago, Dunedin, New Zealand. Dec., 1919.
- BERKEY, CHARLES P., Columbia University, New York, N. Y. August, 1901.
- BERRY, EDWARD WILBER, Johns Hopkins University, Baltimore, Md. Dec., 1909.
- BEYER, SAMUEL WALKER, Iowa Agricultural College, Ames, Iowa. Dec., 1896.
- BILLINGSLEY, PAUL, Anaconda Copper Mining Co., Portage, Wash. Dec., 1922.
- BLACKWELDER, ELIOT, Leland Stanford Jr. University, Stanford University, Calif. December, 1908.
- BOUTWELL, JOHN M., Natl. Copper Bank, Salt Lake City, Utah. Dec., 1905.
- BOWEN, CHARLES F., c/o Standard Oil Co., 26 Broadway, New York City. December, 1916.
- BOWEN, N. L., Geophysical Laboratory, Washington, D. C. December, 1917.
- BOWIE, WILLIAM, U. S. Coast and Geodetic Survey, Washington, D. C. December, 1919.
- BOWNOCKER, JOHN ADAMS, Ohio State University, Columbus, Ohio. Dec., 1904.
- BRANSON, EDWIN BAYER, University of Missouri, Columbia, Mo. Dec., 1911.
- BRETZ, J. H., University of Chicago, Chicago, Ill. December, 1917.
- BRIGHAM, ALBERT PERRY, Colgate University, Hamilton, N. Y. December, 1893.
- BROCK, REGINALD W., Univ. of British Columbia, Vancouver, B. C. Dec., 1904.
- BRODERICK, T. MONTEITH, Calumet and Hecla Mining Co., Calumet, Mich. December, 1921.
- BROKAW, A. D., 157 Maplewood Ave., Maplewood, N. J. December, 1920.
- BROOKS, ALFRED HULSE, U. S. Geological Survey, Washington, D. C. Aug., 1899.
- BROWN, BARNUM, American Museum of Natural History, New York, N. Y. December, 1910.
- BROWN, CHARLES WILSON, Brown University, Providence, R. I. Dec., 1908.
- BROWN, JOHN STAFFORD, U. S. Geol. Survey, Washington, D. C. Dec., 1922.
- BROWN, THOMAS CLACHAR, Laurel Bank Farm, Fitchburg, Mass. Dec., 1915.
- BRUCE, E. L., Geological Survey of Canada, Ottawa, Canada. Dec., 1920.
- BRYAN, KIRK, U. S. Geological Survey, Washington, D. C. December, 1922.
- BUCHER, W. H., University of Cincinnati, Cincinnati, Ohio. December, 1920.
- BUDDINGTON, A. F., 124 Pyne Hall, Princeton, N. J. December, 1919.
- BUEHLER, HENRY ANDREW, Rolla, Mo. December, 1909.
- BURCHARD, E. F., U. S. Geological Survey, Washington, D. C. December, 1920.
- BURLING, LANCASTER D., Whitehall Petr. Corp., 53 Parliament St., Westminster, S. W. I., London, England. December, 1917.
- BURWASH, EDWARD M. J., 556 Bathurst St., Toronto, Canada. Dec., 1916.
- BUTLER, BERT S., Box 277, Calumet, Mich. December, 1912.
- BUTLER, G. MONTAGUE, College of Mines, Tucson, Arizona. December, 1911.
- BUTTS, CHARLES, U. S. Geological Survey, Washington, D. C. December, 1912.
- BUWALDA, J. P., University of California, Berkeley, Calif. December, 1920.
- CADY, G. H., Fayetteville, Ark. December, 1920.
- CALHOUN, FRED HARVEY HALL, Clemson College, S. C. December, 1909.

- CALKINS, FRANK C., U. S. Geological Survey, Washington, D. C. Dec., 1914.
- CAMPBELL, HENRY D., Washington and Lee Univ., Lexington, Va. May, 1889.
- CAMPBELL, MARIUS R., U. S. Geological Survey, Washington, D. C. Aug., 1892.
- CAMPOS, LUIZ FILIPPE G. DE, Geological Survey of Brazil, Rio de Janeiro, Brazil. December, 1917.
- CAMSELL, CHARLES, Department of Mines, Ottawa, Canada. December, 1914.
- CAPPS, STEPHEN R., JR., U. S. Geological Survey, Washington, D. C. Dec., 1911.
- CARMAN, J. ERNEST, Ohio State University, Columbus, Ohio. December, 1917.
- CARNEY, FRANK, Box 309, Eldorado, Kans. December, 1908.
- CASE, ERMINE C., University of Michigan, Ann Arbor, Mich. December, 1901.
- CHADWICK, GEORGE H., University of Rochester, Rochester, N. Y. Dec., 1911.
- CHAMBERLIN, ROLLIN T., University of Chicago, Chicago, Ill. December, 1913.
- *CHAMBERLIN, T. C., University of Chicago, Chicago, Ill.
- CLAPP, CHARLES H., State University, Missoula, Mont. December, 1914.
- CLAPP, FREDERICK G., 30 Church St., New York City. December, 1905.
- CLARK, BRUCE L., Bacon Hall, Univ. of California, Berkeley, Calif. Dec., 1918.
- CLARK, F. R., U. S. Geological Survey, Washington, D. C. December, 1919.
- CLARK, W. O., Pahala, Kau, Hawaii. December, 1920.
- CLARKE, JOHN MASON, Education Building, Albany, N. Y. December, 1897.
- CLELAND, HERDMAN F., Williams College, Williamstown, Mass. Dec., 1905.
- CLEMENTS, J. MORGAN, 20 Broad St., New York City. December, 1894.
- COBB, COLLIER, University of North Carolina, Chapel Hill, N. C. Dec., 1894.
- COLEMAN, ARTHUR P., Toronto University, Toronto, Canada. December, 1896.
- COLLIE, GEORGE L., Beloit College, Beloit, Wis. December, 1897.
- COLLINS, WILLIAM H., Geological Survey, Ottawa, Canada. December, 1921.
- COLLIER, ARTHUR J., U. S. Geological Survey, Washington, D. C. June, 1902.
- CONDIT, D. DALE, c/o Alliance Bank, Calcutta, India. December, 1916.
- COOK, CHARLES W., University of Michigan, Ann Arbor, Mich. Dec., 1915.
- COOKE, C. WYTHE, U. S. Geological Survey, Washington, D. C. Dec., 1918.
- COSTE, EUGENE, 622 Dallas County State Bank Bldg., Dallas, Texas. Dec., 1906.
- CRAWFORD, RALPH DIXON, 1050 Tenth St., Boulder, Colo. December, 1916.
- CROOK, ALJA R., State Museum of Natural History, Springfield, Ill. Dec., 1898.
- *CROSBY, WILLIAM O., Massachusetts Institute of Technology, Boston, Mass.
- CROSS, WHITMAN, 101 East Kirke St., Chevy Chase, Md. May, 1889.
- CULVER, GARRY E., 310 Center Ave., Stevens Point, Wis. December, 1891.
- CUMINGS, EDGAR R., Indiana University, Bloomington, Ind. August, 1901.
- CUSHMAN, J. A., Sharon, Mass. December, 1919.
- DAKE, C. L., Missouri School of Mines, Rolla, Mo. December, 1920.
- DALE, N. C., Hamilton College, Clinton, N. Y. December, 1920.
- DALY, REGINALD A., Harvard University, Cambridge, Mass. December, 1905.
- DANA, EDWARD SALISBURY, Yale University, New Haven, Conn. Dec., 1908.
- *DARTON, NELSON H., U. S. Geological Survey, Washington, D. C.
- DAVIS, E. F., 343 Sansome St., San Francisco, Calif. December, 1920.
- *DAVIS, WILLIAM M., 31 Hawthorne St., Cambridge, Mass.
- DAY, ARTHUR LOUIS, Geophysical Laboratory, Washington, D. C. Dec., 1909.
- DAY, DAVID T., 1333 F St. N. W., Washington, D. C. August, 1891.
- DEAN, BASHFORD, Columbia University, New York, N. Y. December, 1910.
- DE GOLYER, E. L., 65 Broadway, New York, N. Y. December, 1918.
- DEUSSEN, ALEXANDER, 504 Stewart Bldg., Houston, Texas. December, 1916.

- DE WOLF, FRANK W., Great Southern Life Bldg., Dallas, Texas. Dec., 1909.
- DICKERSON, ROY E., Masonic Temple Building, Manila, P. I. December, 1918.
- *DILLER, JOSEPH S., U. S. Geological Survey, Washington, D. C.
- D'INVILLIERS, EDWARD V., 518 Walnut St., Philadelphia, Pa. December, 1888.
- DODGE, RICHARD E., Storrs, Conn. August, 1897.
- DOLMAGE, VICTOR, Canadian Geological Survey, Ottawa, Canada. Dec., 1922.
- DRAKE, NOAH FIELDS, Fayetteville, Arkansas. December, 1898.
- DRESSER, JOHN A., 701 Eastern Townships Bank Bldg., Montreal, Canada. December, 1906.
- *DUMBLE, EDWIN T., 316 Pacific Bldg., Houston, Texas.
- DUNBAR, C. O., Yale University, New Haven, Conn. December, 1920.
- EAKLE, ARTHUR S., University of California, Berkeley, Calif. December, 1899.
- ECKEL,⁴ EDWIN C., 1503 Decatur St. N. W., Washington, D. C. Dec., 1905.
- EMERY, WILSON B., Casper, Wyoming. December, 1919.
- *EMERSON, BENJAMIN K., Amherst, Mass.
- EMMONS, WILLIAM H., Univ. of Minnesota, Minneapolis, Minn. Dec., 1912.
- *FAIRCHILD, HERMAN L., University of Rochester, Rochester, N. Y.
- FARRINGTON, OLIVER C., Field Museum of Natural History, Chicago, Ill. December, 1895.
- FATH, A. E., U. S. Geological Survey, Washington, D. C. December, 1920.
- FENNEMAN, NEVIN M., University of Cincinnati, Cincinnati, Ohio. Dec., 1904.
- FENNER, CLARENCE N., Geophysical Laboratory, Washington, D. C. Dec., 1911.
- FERGUSON, H. G., U. S. Geological Survey, Washington, D. C. December, 1920.
- FISHER, CASSIUS ASA, 705 First Natl. Bank Bldg., Denver, Colo. Dec., 1908.
- FOERSTE, AUGUST F., 129 Wroe Ave., Dayton, Ohio. December, 1899.
- FORD, WILLIAM E., Sheffield Scientific School, New Haven, Conn. Dec., 1915.
- FOYE, W. G., Wesleyan University, Middletown, Conn. December, 1919.
- FULLER, MYRON L., 60 Main St., Brockton, Mass. December, 1898.
- GALLOWAY, J. J., Columbia University, New York, N. Y. December, 1920.
- GALPIN, SIDNEY L., 630 Park Ave., Ames, Iowa. December, 1917.
- GANE, HENRY STEWART, R. D. No. 1, Santa Barbara, Calif. December, 1896.
- GARDNER, JAMES H., 626 Kennedy Building, Tulsa, Okla. December, 1911.
- GARDNER, JULIA A., U. S. Geological Survey, Washington, D. C. Dec., 1920.
- GEORGE, RUSSELL D., University of Colorado, Boulder, Colo. December, 1906.
- GIDLEY, JAMES WILLIAM, U. S. Nat'l Museum, Washington, D. C. Dec., 1922.
- GILES, ALBERT W., University of Virginia, University, Va. December, 1921.
- GILL, ADAM CAPEN, Cornell University, Ithaca, N. Y. December, 1888.
- GLENN, L. C., 2111 Garland Ave., Nashville, Tenn. June, 1900.
- GOLDMAN, MARCUS ISAAC, U. S. Geol. Survey, Washington, D. C. Dec., 1916.
- GOLDRING, WINIFRED, New York State Museum, Albany, N. Y. Dec., 1921.
- GOLDTHWAIT, JAMES WALTER, Dartmouth College, Hanover, N. H. Dec., 1909.
- GORDON, CHARLES H., University Library, University of Tennessee, Knoxville, Tenn. August, 1893.
- GORDON, CLARENCE E., Massachusetts Agricultural College, Amherst, Mass. December, 1913.
- GOULD, CHARLES N., 1218 Colcord Bldg., Oklahoma City, Okla. Dec., 1904.
- GRABAU, AMADEUS W., Government University, Peking, China. Dec., 1898.
- GRANGER, WALTER, American Museum of Natural History, New York, N. Y. December, 1911.

- GRANT, ULYSSES SHERMAN, Northwestern Univ., Evanston, Ill. Dec., 1890.
- GRASTY, JOHN SHARSHALL, Box 458, Charlottesville, Va. December, 1911.
- GRATON, LOUIS C., Foxcroft House, Cambridge, 38, Mass. December, 1913.
- GREGORY, HERBERT E., Yale University, New Haven, Conn. August, 1901.
- GREENE, FRANK COOK, 1434 S. Cincinnati Ave., Tulsa, Okla. December, 1917.
- GRIMSLEY, GEORGE P., 16 York Court, Baltimore, Md. August, 1895.
- GROUT, FRANK F., University of Minnesota, Minneapolis, Minn. Dec., 1918.
- GURLEY, WILLIAM F. E. R., University of Chicago, Chicago, Ill. Dec., 1914.
- HALBERSTADT, BAIRD, Pottsville, Pa. December, 1909.
- HANCE, J. H., 708 W. Washington Boulevard, Urbana, Ill. December, 1920.
- HANCOCK, E. T., U. S. Geological Survey, Washington, D. C. December, 1919.
- HARDER, E. C., 1111 Harrison Building, Philadelphia, Pa. December, 1918.
- HARES, C. J., The Ohio Oil Co., Casper, Wyo. December, 1920.
- HARRIS, GILBERT D., Cornell University, Ithaca, N. Y. December, 1903.
- HARRISON, JOHN BURCHMORE, Georgetown, British Guiana. June, 1902.
- HARTNAGEL, CHRIS A., Education Building, Albany, N. Y. December, 1913.
- HASTINGS, JOHN B., 5456 Sierra Vista Ave., Los Angeles, Calif. May, 1889.
- *HAWORTH, ERASMUS, University of Kansas, Lawrence, Kans.
- HAY, OLIVER P., Carnegie Institution, Washington, D. C. December, 1921.
- HAYES, ALBERT O., c/o Carr Bros., Inc., 65 Broadway, N. Y. City. Dec., 1919.
- HEALD, K. C., U. S. Geological Survey, Washington, D. C. December, 1920.
- HENNEN, RAY V., 1604 Benedum-Trees Bldg., Pittsburgh, Pa. December, 1914.
- HERSHEY, OSCAR H., Crocker Building, San Francisco, Calif. December, 1909.
- HESS, FRANK L., U. S. Geological Survey, Washington, D. C. December, 1921.
- HEWETT, DONNEL F., U. S. Geological Survey, Washington, D. C. Dec., 1916.
- HICE, RICHARD R., Beaver, Pa. December, 1903.
- HILL, J. M., U. S. Geological Survey, Washington, D. C. December, 1920.
- *HILL, ROBERT T., Room 816, Magnolia Bldg., Dallas, Texas.
- HILLS, RICHARD C., Denver, Colo. August, 1894.
- HINDS, HENRY, 1153 Laurel Ave., St. Paul, Minn. December, 1912.
- HINTZE, FERDINAND FRIIS, 580 Corona St., Denver, Colo. December, 1917.
- HOBBS, WILLIAM H., University of Michigan, Ann Arbor, Mich. August, 1891.
- HOLDEN, ROY J., Virginia Polytechnic Institute, Blacksburg, Va. Dec., 1914.
- HOLLAND, WILLIAM JACOB, Carnegie Museum, Pittsburgh, Pa. December, 1910.
- HOLLICK, ARTHUR, N. Y. Botanical Garden, New York, N. Y. August, 1898.
- HOPKINS, O. B., International Petroleum Co., Ltd., 56 Church St., Toronto, Canada. December, 1919.
- HOPKINS, THOMAS C., Syracuse University, Syracuse, N. Y. December, 1894.
- HOTCHKISS, WILLIAM OTIS, State Geological Survey, Madison, Wis. Dec., 1911.
- *HOVEY, EDMUND OTIS, American Museum of Natural History, New York, N. Y.
- HOWE, ERNEST, Litchfield, Conn. December, 1903.
- HUBBARD, GEORGE D., Oberlin College, Oberlin, Ohio. December, 1914.
- HUDSON, GEORGE H., Plattsburg Normal School, Plattsburg, N. Y. Dec., 1917.
- HUNT, WALTER F., University of Michigan, Ann Arbor, Mich. December, 1914.
- HUNTINGTON, ELLSWORTH, Yale University, New Haven, Conn. Dec., 1906.
- HUSSAKOF, LOUIS, American Museum of Natural History, New York, N. Y. December, 1910.
- HYDE, J. E., Western Reserve University, Cleveland, Ohio. December, 1916.
- JACKSON, ROBERT T., Peterborough, N. H. August, 1894.

- JACOBS, ELBRIDGE C., University of Vermont, Burlington, Vt. December, 1921.
- JAGGAR, THOMAS AUGUSTUS, JR., Hawaiian Volcano Observatory, Territory of Hawaii, U. S. A. December, 1906.
- JEFFERSON, MARK S. W., Michigan State Normal College, Ypsilanti, Mich. December, 1904.
- JEFFREY, EDWARD C., Harvard University, Cambridge, Mass. December, 1914.
- JENKINS, OLAF P., State College, Pullman, Wash. December, 1921.
- JOHANNSEN, ALBERT, University of Chicago, Chicago, Ill. December, 1908.
- JOHNSON, B. L., U. S. Geological Survey, Washington, D. C. December, 1919.
- JOHNSON, DOUGLAS WILSON, Columbia University, New York, N. Y. Dec., 1906.
- JOHNSON, ROSWELL H., University of Pittsburgh, Pittsburgh, Pa. Dec., 1918.
- JONAS, ANNA L., Bridgeton, N. J. December, 1922.
- KATZ, FRANK JAMES, U. S. Geological Survey, Washington, D. C. Dec., 1912.
- KAY, GEORGE FREDERICK, State Univ. of Iowa, Iowa City, Iowa. Dec., 1908.
- KEITH, ARTHUR, U. S. Geological Survey, Washington, D. C. May, 1889.
- *KEMP, JAMES F., Columbia University, New York, N. Y.
- KEW, W. S. W., 901 S. Norton Ave., Los Angeles, Calif. December, 1920.
- KEYES, CHARLES ROLLIN, 944 Fifth St., Des Moines, Iowa. August, 1890.
- KINDLE, EDWARD M., Victoria Memorial Museum, Ottawa, Canada. Dec., 1905.
- KIRK, CHARLES T., Box 1592, Tulsa, Okla. December, 1915.
- KIRK, EDWIN, U. S. Geological Survey, Washington, D. C. December, 1912.
- KNIGHT, CYRIL WORKMAN, Toronto, Ontario, Canada. December, 1911.
- KNOPE, ADOLPH, Yale Station, New Haven, Conn. December, 1911.
- KNOPE, ELEANORA BLISS, 105 East Rock Road, New Haven, Conn. Dec., 1919.
- KNOWLTON, FRANK H., U. S. National Museum, Washington, D. C. May, 1889.
- KRAUS, EDWARD HENRY, University of Michigan, Ann Arbor, Mich. June, 1902.
- KUMMEL, HENRY B., Trenton, N. J. December, 1895.
- *KUNZ, GEORGE F., 401 Fifth Ave., New York, N. Y.
- LAHEE, FREDERIC H., Sun Co., Dallas, Texas. December, 1917.
- LANDES, HENRY, University of Washington, University Station, Seattle, Wash. December, 1908.
- LANE, ALFRED C., Tufts College, Mass. December, 1889.
- LARSEN, ESPER S., JR., U. S. Geological Survey, Washington, D. C. Dec., 1914.
- LAWSON, ANDREW C., University of California, Berkeley, Cal. May, 1889.
- LEE, WILLIS THOMAS, U. S. Geological Survey, Washington, D. C. Dec., 1903.
- LEES, JAMES H., Iowa Geological Survey, Des Moines, Iowa. December, 1914.
- LEIGHTON, MORRIS M., University of Illinois, Urbana, Ill. December, 1921.
- LEITH, CHARLES K., University of Wisconsin, Madison, Wis. Dec., 1902.
- LEONARD, ARTHUR G., State University of North Dakota, Grand Forks, N. Dak. December, 1901.
- LEVERETT, FRANK, Ann Arbor, Mich. August, 1890.
- LEWIS, J. VOLNEY, Rutgers College, New Brunswick, N. J. December, 1906.
- LIBBEY, WILLIAM, Princeton University, Princeton, N. J. August, 1899.
- LIDDLE, R. A., Standard Oil Company of Venezuela, Caracas, Venezuela, South America. December, 1921.
- LINDGREN, WALDEMAR, Massachusetts Institute of Technology, Cambridge, Mass. August, 1890.
- LISBOA, MIGUEL A. R., Caixa postal 829, Ave. Rio Branco 46-V, Rio de Janeiro, Brazil. December, 1913.

- LITTLE, HOMER P., Clark University, Worcester, Mass. December, 1918.
- LLOYD, E. R., c/o Mid Kansas Oil and Gas Co., Mineral Wells, Texas. December, 1919.
- LOGAN, WILLIAM N., Indiana University, Bloomington, Ind. December, 1917.
- LOOMIS, FREDERICK BREWSTER, Amherst College, Amherst, Mass. Dec., 1909.
- LOUDERBACK, GEORGE D., University of California, Berkeley, Calif. June, 1902.
- LOUGHLIN, GERALD F., U. S. Geological Survey, Washington, D. C. Dec., 1916.
- LOW, ALBERT P., 154 McLaren St., Ottawa, Canada. December, 1905.
- LULL, RICHARD SWANN, Yale University, New Haven, Conn. December, 1909.
- LUPTON, CHARLES T., 611 17th St., Denver, Colo. December, 1916.
- MCCALLIE, SAMUEL WASHINGTON, Atlanta, Ga. December, 1909.
- MCCASKEY, HIRAM D., Central Point, Oregon. December, 1904.
- MCCONNELL, RICHARD G., Rideau Club, Ottawa, Canada. May, 1889.
- MCCOY, ALEXANDER WATTS, Bartlesville, Okla. December, 1922.
- MACDONALD, DONALD F., 45 Nassau St., New York, N. Y. December, 1915.
- MACFARLANE, JAMES RIEMAN, Woodland Road, Pittsburgh, Pa. August, 1891.
- MCINNES, WILLIAM, Geological and Natural History Survey of Canada, Ottawa, Canada. May, 1889.
- MACKAY, BERTRAM REID, Geol. Survey of Canada, Ottawa, Canada. Dec., 1922.
- McKELLAR, PETER, Fort William, Ontario, Canada. August, 1890.
- MCLAUGHLIN, DONALD H., 1629 Euclid Ave., Berkeley, Calif. December, 1922.
- MANSFIELD, GEORGE R., 2067 Park Rd., N. W., Washington, D. C. Dec., 1909.
- MARBUT, CURTIS F., Bureau of Soils, Washington, D. C. August, 1897.
- MARSTERS, VERNON F., 920 Grande Ave., Hayes Building, Kansas City, Mo. August, 1892.
- MARTIN, GEORGE C., U. S. Geological Survey, Washington, D. C. June, 1902.
- MARTIN, LAWRENCE, Dept. of State, Room 381, Washington, D. C. Dec., 1909.
- MATHER, KIRTLEY F., Denison University, Granville, Ohio. December, 1918.
- MATHEWS, EDWARD B., Johns Hopkins University, Baltimore, Md. Aug., 1895.
- MATSON, GEORGE C., 408 Cosden Bldg., Tulsa, Okla. December, 1918.
- MATTHES, FRANCOIS E., U. S. Geol. Survey, Washington, D. C. Dec., 1914.
- MATTHEW, W. D., American Museum of Natural History, New York, N. Y. December, 1903.
- MAURY, CARLOTTA J., Hastings-on-Hudson, N. Y. December, 1920.
- MAYNARD, THOMAS POOLE, 1622 D. Hurt Bldg., Atlanta, Ga. December, 1914.
- MEAD, WARREN JUDSON, University of Wisconsin, Madison, Wis. Dec., 1916.
- MEHL, MAURICE G., University of Missouri, Columbia, Mo. December, 1922.
- MEINZER, OSCAR E., U. S. Geological Survey, Washington, D. C. Dec., 1916.
- MENDENHALL, WALTER C., U. S. Geol. Survey, Washington, D. C. June, 1902.
- MERRIAM, JOHN C., Carnegie Institution, Washington, D. C. August, 1895.
- MERRILL, GEORGE P., U. S. National Museum, Washington, D. C. Dec., 1888.
- MERWIN, HERBERT E., Geophysical Laboratory, Washington, D. C. Dec., 1914.
- MILLER, ARTHUR M., State University of Kentucky, Lexington, Ky. Dec., 1897.
- MILLER, BENJAMIN L., Lehigh University, South Bethlehem, Pa. Dec., 1904.
- MILLER, WILLET G., Toronto, Canada. December, 1902.
- MILLER, WILLIAM JOHN, Smith College, Northampton, Mass. December, 1909.
- MISER, HUGH D., U. S. Geological Survey, Washington, D. C. December, 1916.
- MOFFIT, FRED HOWARD, U. S. Geological Survey, Washington, D. C. Dec., 1912.

- MOLENGRAAF, G. A. F., Technical High School, Delft, Holland. Dec., 1913.
- MOOK, CHARLES CRAIG, Metuchen, N. J. December, 1922.
- MOORE, ELWOOD S., University of Toronto, Toronto, Canada. December, 1911.
- MOORE, RAYMOND C., University of Kansas, Lawrence, Kans. December, 1921.
- MUNN, MALCOLM JOHN, Clinton Bldg., Tulsa, Okla. December, 1909.
- *NASON, FRANK L., West Haven, Conn.
- NELSON, W. A., Tennessee Geological Survey, Nashville, Tenn. Dec., 1920.
- NEWLAND, DAVID HALE, Albany, N. Y. December, 1906.
- NEWSOM, JOHN F., Leland Stanford, Jr., University, Stanford University, Calif. December, 1899.
- NOBLE, LEVI F., Valyermo, Calif. December, 1916.
- NORTON, WILLIAM H., Cornell College, Mount Vernon, Iowa. December, 1895.
- NORWOOD, CHARLES J., State University, Lexington, Ky. August, 1894.
- O'CONNELL, MARJORIE, American Museum of Natural History, New York, N. Y. December, 1919.
- Ogilvie, IDA HELEN, Barnard College, Columbia University, New York, N. Y. December, 1906.
- O'HARA, CLEOPHAS C., South Dakota School of Mines, Rapid City, S. Dak. December, 1904.
- OHERN, DANIEL WEBSTER, 515 W. 14th St., Oklahoma City, Okla. Dec., 1911.
- OLIVEIRA, E. P. DE, Geol. Survey of Brazil, Rio de Janeiro, Brazil. Dec., 1918.
- O'NEILL, J. J., Geological Survey of Canada, Ottawa, Canada. Dec., 1920.
- OSBORN, HENRY F., American Museum of Natural History, New York, N. Y. August, 1894.
- OVERBECK, ROBERT M., 834 Ocean Ave., Long Beach, Calif. December, 1921.
- PACK, ROBERT W., American Exchange National Bank Bldg., Dallas, Texas. December, 1916.
- P'AIGE, SIDNEY, U. S. Geological Survey, Washington, D. C. December, 1911.
- P'ALACHE, CHARLES, Harvard University, Cambridge, Mass. August, 1897.
- PARKS, WILLIAM A., University of Toronto, Toronto, Canada. Dec., 1906.
- *PATTON, HORACE B., 3149 West 44th St., Denver, Colo.
- PECK, FREDERICK B., Lafayette College, Easton, Pa. August, 1901.
- PENROSE, RICHARD A. F., JR., 460 Bullitt Bldg., Philadelphia, Pa. May, 1889.
- PERKINS, GEORGE H., University of Vermont, Burlington, Vt. June, 1902.
- PERRY, JOSEPH H., 276 Highland St., Worcester, Mass. December, 1888.
- PHALEN, WILLIAM C., The Solvay Process, Syracuse, N. Y. December, 1912.
- PHILLIPS, ALEXANDER H., Princeton University, Princeton, N. J. Dec., 1914.
- POGUE, JOSEPH E., 42 West 12th St., New York, N. Y. December, 1911.
- POWERS, SIDNEY, Amerada Petr. Co., P. O. Box 2022, Tulsa, Okla. Dec., 1920.
- PRATT, JOSEPH H., North Carolina Geol. Survey, Chapel Hill, N. C. Dec., 1898.
- PRATT, W. E., Humble Oil and Refining Co., Houston, Texas. Dec., 1920.
- PRICE, WILLIAM A., JR., 626 West Bldg., Houston, Texas. December, 1916.
- PRINDLE, LOUIS M., U. S. Geological Survey, Washington, D. C. Dec., 1912.
- PROUTY, WILLIAM F., Univ. of North Carolina, Chapel Hill, N. C. Dec., 1911.
- *PUMPELLE, RAPHAEL, Newport, R. I.
- QUIRKE, TERENCE T., University of Illinois, Urbana, Ill. December, 1921.
- RANSOME, FREDERICK L., U. S. Geol. Survey, Washington, D. C. August, 1895.
- RAYMOND, PERCY EDWARD, Museum of Comparative Zoölogy, Cambridge, Mass. December, 1907.

- REEDS, CHESTER A., American Museum of Natural History, New York, N. Y. December, 1913.
- REESIDE, JOHN B., JR., U. S. Geological Survey, Hyattsville, Md. Dec., 1921.
- REGER, DAVID B., Box 816, Morgantown, W. Va. December, 1918.
- REID, HARRY FIELDING, Johns Hopkins University, Baltimore, Md. Dec., 1892.
- REINECKE, LEOPOLD, c/o P. A. Williams, Loanda, Angola, S. W. Africa. December, 1916.
- RICE, WILLIAM NORTH, Wesleyan University, Middletown, Conn. August, 1890.
- RICH, JOHN LYON, P. O. Box 294, Iola, Kans. December, 1912.
- RICHARDS, R. W., U. S. Geological Survey, Washington, D. C. December, 1920.
- RICHARDSON, CHARLES H., Syracuse University, Syracuse, N. Y. Dec., 1899.
- RICHARDSON, GEORGE B., U. S. Geol. Survey, Washington, D. C. Dec., 1908.
- RIES, HEINRICH, Cornell University, Ithaca, N. Y. December, 1893.
- RIGGS, ELMER S., Field Museum of Natural History, Chicago, Ill. Dec., 1911.
- ROBINSON, HENRY HOLLISTER, Hopkins Hall, New Haven, Conn. Dec., 1916.
- RODDY, H. J., State Normal School, Millersville, Pa. December, 1919.
- ROGERS, AUSTIN F., Stanford University, Calif. December, 1918.
- ROSE, BRUCE, Dept. of Geology, Queens Univ., Kingston, Ontario. Dec., 1916.
- RUEDEMANN, RUDOLF, Albany, N. Y. December, 1905.
- RUTLEDGE, JOHN J., 22 Light St., Baltimore, Md. December, 1911.
- SALES, RENO H., Anaconda Copper Mining Company, Butte, Mont. Dec., 1916.
- SAYLES, ROBERT WILCOX, Harvard University, Chestnut Hill, Mass. Dec., 1917.
- SARDESON, FREDERICK W., Univ. of Minnesota, Minneapolis, Minn. Dec., 1892.
- SAVAGE, THOMAS EDMUND, University of Illinois, Urbana, Ill. December, 1907.
- SCHALLER, WALDEMAR T., U. S. Geol. Survey, Washington, D. C. Dec., 1918.
- SCHOFIELD, S. J., University of British Columbia, Vancouver, B. C. Dec., 1918.
- SCHRADER, FRANK C., U. S. Geological Survey, Washington, D. C. Aug., 1901.
- SCHUCHERT, CHARLES, Yale University, New Haven, Conn. August, 1895.
- SCHULTZ, ALFRED R., Hudson, Wis. December, 1912.
- SCOTT, WILLIAM B., Princeton University, Princeton, N. J. August, 1892.
- SEAMAN, ARTHUR E., Michigan College of Mines, Houghton, Mich. Dec., 1904.
- SELLARDS, ELIAS H., University of Texas, Austin, Texas. December, 1905.
- SEMMES, DOUGLAS R., Apartado Postal, 150 Tampico, Tamps, Mexico. December, 1921.
- SHALER, MILLARD K., 66 Rue Des Colonies, Brussels, Belgium. Dec., 1914.
- SHANNON, CHARLES W., Oklahoma Geol. Survey, Norman, Okla. Dec., 1918.
- SHATTUCK, GEORGE BURBANK, Poughkeepsie, N. Y. August, 1899.
- SHAW, EUGENE W., 11 Taylor St., Chevy Chase, Md. December, 1912.
- SHEDD, SOLON, State College of Washington, Pullman, Wash. December, 1904.
- SHEPARD, EDWARD M., 1403 Benton Ave., Springfield, Mo. August, 1901.
- SHIMEK, BOHUMIL, University of Iowa, Iowa City, Iowa. December, 1904.
- SHIMER, HERVEY WOODBURN, Massachusetts Institute of Technology, Cambridge, Mass. December, 1910.
- SHULER, E. W., South Methodist University, Dallas, Texas. December, 1920.
- SIEBENTHAL, CLAUDE E., U. S. Geol. Survey, Washington, D. C. Dec., 1912.
- *SIMONDS, FREDERICK W., University of Texas, Austin, Texas.
- SINCLAIR, WILLIAM JOHN, Princeton University, Princeton, N. J. Dec., 1906.
- SINGEWALD, JOSEPH T., Johns Hopkins University, Baltimore, Md. Dec., 1911.
- SLOAN, EARLE, Charleston, S. C. December, 1908.

- SMITH, BURNETT, Syracuse University, Skaneateles, N. Y. December, 1911.
 SMITH, CARL, Box 1136, Tulsa, Okla. December, 1912.
 *SMITH, EUGENE A., University of Alabama, University, Ala.
 SMITH, GEORGE OTIS, U. S. Geological Survey, Washington, D. C. Aug., 1897.
 SMITH, PHILIP S., U. S. Geological Survey, Washington, D. C. Dec., 1909.
 SMITH, RICHARD A., Biological Survey of Michigan, Lansing, Mich. Dec., 1921.
 SMITH, STANLEY, University, Bristol, England. December, 1922.
 SMITH, WARREN DU PRÉ, University of Oregon, Eugene, Ore. December, 1909.
 SMITH, W. S. TANGIER, 640 Tennyson Ave., Palo Alto, Calif. June, 1902.
 *SMOCK, JOHN C., Hudson, N. Y.
 SMYTH, CHARLES H., JR., Princeton University, Princeton, N. J. Aug., 1892.
 SMYTH, HENRY L., Harvard University, Cambridge, Mass. August, 1894.
 SOMERS, R. E., Oil and Gas Bldg., University of Pittsburgh, Pittsburgh, Pa.
 December, 1919.
 SOPER, EDGAR K., 120 Broadway, New York City, Room 3101. December, 1918.
 SOSMAN, R. B., Geophysical Laboratory, Washington, D. C. December, 1920.
 SPEIGHT, ROBERT, Christ Church, Canterbury College, New Zealand. Dec., 1916.
 SPENCER, ARTHUR COE, U. S. Geological Survey, Washington, D. C. Dec., 1896.
 SPRINGER, FRANK, U. S. National Museum, Washington, D. C. December, 1911.
 SPURR, JOSIAH E., c/o Engineering and Mining Journal, 10th Ave. and 36th
 St., New York, N. Y. December, 1894.
 STANLEY-BROWN, JOSEPH, 26 Exchange Place, New York, N. Y. August, 1892.
 STANTON, TIMOTHY W., U. S. National Museum, Washington, D. C. Aug., 1891.
 STAUFFER, CLINTON R., Univ. of Minnesota, Minneapolis, Minn. Dec., 1911.
 STEBINGER, EUGENE, JR., 18 Broadway, New York, N. Y. December, 1916.
 STEIDTMANN, EDWARD, University of Wisconsin, Madison, Wis. Dec., 1916.
 STEPHENSON, LLOYD W., U. S. Geol. Survey, Washington, D. C. Dec., 1911.
 *STEVENSON, JOHN J., 215 West 101st St., New York, N. Y.
 STOLLER, JAMES HOUGH, Union College, Schenectady, N. Y. December, 1917
 STONE, RALPH WALTER, State Geological Survey, Harrisburg, Pa. Dec., 1912.
 STOSE, GEORGE WILLIS, U. S. Geological Survey, Washington, D. C. Dec., 1908.
 STOUT, WILBER, Geological Survey of Ohio, Columbus, Ohio. December, 1918.
 SWARTZ, CHARLES K., Johns Hopkins University, Baltimore, Md. Dec., 1908.
 TABER, STEPHEN, University of South Carolina, Columbia, S. C. Dec., 1914.
 TAFF, JOSEPH A., 781 Flood Building, San Francisco, Calif. August, 1895.
 TALBOT, MIGNON, Mount Holyoke College, South Hadley, Mass. Dec., 1913.
 TALMAGE, JAMES E., 47 E. So. Temple St., Salt Lake City, Utah. Dec., 1897.
 TARR, WILLIAM ARTHUR, University of Missouri, Columbia, Mo. Dec., 1917.
 TAYLOR, FRANK B., Fort Wayne, Ind. December, 1895.
 THOMAS, ABRAM O., University of Iowa, Iowa City, Iowa. December, 1921.
 TILTON, J. L., Morgantown, W. Va. December, 1920.
 TOMLINSON, CHARLES WELDON, 1610 Bixby Ave., Ardmore, Okla. Dec., 1917.
 TROWBRIDGE, ARTHUR C., University of Iowa, Iowa City, Iowa. Dec., 1913.
 *TURNER, HENRY W., Mills Building, San Francisco, Calif.
 TWENHOFEL, WILLIAM H., University of Wisconsin, Madison, Wis. Dec., 1913.
 TWITCHELL, MAYVILLE W., State Geological Survey, Trenton, N. J. Dec., 1911.
 TYRRELL, JOSEPH B., Confederation Life Bldg., Toronto, Canada. May, 1889.
 UDDEN, JOHAN A., University of Texas, Austin, Texas. August, 1897.

- UGLOW, WILLIAM L., University of British Columbia, Vancouver, Canada. December, 1922.
- ULRICH, EDWARD O., U. S. Geological Survey, Washington, D. C. Dec., 1903.
- UMPLEBY, JOSEPH B., University of Oklahoma, Norman, Okla. Dec., 1913.
- *UPHAM, WARREN, Minnesota Historical Society, St. Paul, Minn.
- VAN HORN, F. R., Case School of Applied Science, Cleveland, Ohio. Dec., 1898.
- VAN INGEN, GILBERT, Princeton University, Princeton, N. J. December, 1904.
- VAN TUYL, FRANCIS M., Colorado School of Mines, Golden, Colo. Dec., 1917.
- VAUGHAN, T. WAYLAND, U. S. Geol. Survey, Washington, D. C. August, 1896.
- VEATCH, ARTHUR CLIFFORD, 7 Central Drive, Port Washington, N. Y. December, 1906.
- WADE, BRUCE, State Geological Survey, Nashville, Tenn. December, 1920.
- *WALCOTT, CHARLES D., Smithsonian Institution, Washington, D. C.
- WALKER, THOMAS L., University of Toronto, Toronto, Canada. Dec., 1903.
- WARING, GERALD A., Port of Spain, Trinidad, B. W. I. December, 1921.
- WARREN, CHARLES H., Massachusetts Institute of Technology, Boston, Mass. December, 1901.
- WASHBURN, C. W., 2 Rector St., New York, N. Y. December, 1919.
- WASHINGTON, HENRY STEPHENS, Geophysical Laboratory, Washington, D. C. August, 1896.
- WATSON, THOMAS L., University of Virginia, Charlottesville, Va. June, 1900.
- WEAVER, CHARLES E., 264 Herkimer Road, Utica, N. Y. December, 1913.
- WEED, WALTER H., Tuckahoe, N. Y. May, 1889.
- WEGEMANN, CARROLL H., 722 East 7th Ave., Denver, Colo. December, 1912.
- WEIDMAN, SAMUEL, 814 Monett St., Norman, Okla. December, 1903.
- WELLER, STUART, University of Chicago, Chicago, Ill. June, 1900.
- WELLS, ROGER C., U. S. Geological Survey, Washington, D. C. Dec., 1921.
- WESTGATE, LEWIS G., 124 Oak Hill Ave., Delaware, Ohio. August, 1894.
- WHERRY, EDGAR T., Bureau of Chemistry, Washington, D. C. Dec., 1915.
- WHITE, DAVID, U. S. National Museum, Washington, D. C. May, 1889.
- *WHITE, ISRAEL C., Morgantown, W. Va.
- WHITLOCK, H. P., American Museum of Natural History, New York, N. Y. December, 1920.
- WIELAND, GEORGE REBER, Yale University, New Haven, Conn. December, 1910.
- WILDER, FRANK A., North Holston. Smyth County, Va. December, 1905.
- *WILLIAMS, EDWARD H., JR., Woodstock, Vt.
- WILLIAMS, IRA A., Oregon Bureau of Mines and Geology, 417 Oregon Bldg., Portland, Ore. December, 1905.
- WILLIAMS, MERTON YARWOOD, Geological Survey, Ottawa, Canada. Dec., 1916.
- WILLIS, BAILEY, Leland Stanford Jr. University, Stanford University, Calif. December, 1889.
- WILSON, ALFRED W. G., Department of Mines, Ottawa, Canada. June, 1902.
- WILSON, MORLEY EVANS, Geological Survey, Ottawa, Canada. December, 1916.
- WINCHELL, ALEXANDER N., University of Wisconsin, Madison, Wis. Aug., 1901.
- *WINCHELL, HORACE VAUGHAN, Pacific Mutual Building, Los Angeles, Calif.
- *WINSLOW, ARTHUR, 131 State St., Boston, Mass.
- WOLFF, JOHN E., Harvard University, Cambridge, Mass. December, 1889.
- WOOD, HARRY OSCAR, Mt. Wilson Observatory, Pasadena, Calif. Dec., 1922.
- WOODMAN, JOSEPH E., New York University, New York, N. Y. Dec., 1905.

- WOODRING, WENDELL P., U. S. Geol. Survey, Washington, D. C. Dec., 1921.
 WOODRUFF, E. G., New England Oil and Pipe Co., Tulsa, Okla. Dec., 1922.
 WOODWARD, ROBERT S., Carnegie Institution, Washington, D. C. May, 1889.
 WOODWORTH, JAY B., Geological Museum, 38 Oxford St., Cambridge, Mass.
 December, 1895.
 WRIGHT, CHARLES WILL, 28 Vie del Parlamento, Rome, Italy. Dec., 1909.
 WRIGHT, FREDERIC E., Geophysical Laboratory, Carnegie Institution, Wash-
 ington, D. C. December, 1903.
 ZIEGLER, VICTOR, Colorado School of Mines, Golden, Colo. December, 1916.

CORRESPONDENTS DECEASED

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|---------------------------------------|---|
| CREDNER, HERMAN. Died July 22, 1913. | SUESS, EDWARD. Died April 20, 1914. |
| MICHEL-LÉVY, A. Died September, 1911. | TSCHERNYSCHIEW, TH. Died Jan. 15, 1914. |
| ROSENBUSCH, H. Died January 20, 1914. | ZIRKEL, FERDINAND. Died June 11, 1912. |

FELLOWS DECEASED

* Indicates Original Fellow (see article III of Constitution)

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| *ASHBURNER, CHAS. A. Died Dec. 24, 1889. | *GILBERT, GROVE K. Died May 1, 1918. |
| BARLOW, ALFRED E. Died May 28, 1914. | GIROUX, N. J. Died November 30, 1891. |
| BARRELL, JOSEPH. Died May 4, 1919. | HAGUE, ARNOLD. Died May 14, 1917. |
| BEECHER, CHARLES E. Died Feb. 14, 1904. | *HALL, CHRISTOPHER W. Died May 10, 1911. |
| *BECKER, GEORGE F. Died April 20, 1919. | *HALL, JAMES. Died August 7, 1898. |
| BELL, ROBERT. Died June 18, 1917. | HATCHER, JOHN B. Died July 3, 1904. |
| BICKMORE, ALBERT S. Died Aug. 12, 1914. | *HAY, ROBERT. Died December 14, 1895. |
| BLAKE, WM. PHIPPS. Died May 21, 1910. | HAYES, C. WILLARD. Died Feb. 9, 1916. |
| BOWMAN, AMOS. Died June 18, 1894. | *HEILPRIN, ANGELO. Died July 17, 1907. |
| BRANNER, JOHN C. Died March 1, 1922. | HILGARD, EUGENE W. Died Jan. 8, 1916. |
| BROWN, AMOS P. Died Oct. 9, 1917. | HILL, FRANK A. Died July 13, 1915. |
| BUCKLEY, ERNEST R. Died Jan. 19, 1912. | *HITCHCOCK, CHAS. H. Died Nov 7, 1919. |
| CAIRNES, D. D. Died June 14, 1917. | *HOLBROOK, LEVI. Died July 26, 1922. |
| *CALVIN, SAMUEL. Died April 17, 1911. | *HOLMES, JOSEPH A. Died July 13, 1915. |
| CARPENTER, FRANK R. Died April 1, 1910. | HONEYMAN, DAVID. Died October 17, 1889. |
| *CHAPIN, J. H. Died March 14, 1892. | *HOWELL, EDWIN E. Died April 16, 1911. |
| CLARK, WILLIAM B. Died July 27, 1917. | *HOVEY, HORACE C. Died July 27, 1914. |
| *CLAYPOLE, EDWARD W. Died Aug. 17, 1901. | HUNT, THOMAS S. Died Feb. 12, 1892. |
| *COMSTOCK, THEO. B. Died July 26, 1915. | *HYATT, ALPHEUS. Died Jan. 15, 1902. |
| COOK, GEORGE H. Died Sept. 22, 1889. | IDDINGS, J. P. Died Sept. 8, 1920. |
| *COPE, EDWARD D. Died April 12, 1897. | IRVING, JOHN D. Died July 26, 1918. |
| COX, GUY H. Died August 20, 1922. | JACKSON, THOMAS M. Died Feb. 3, 1912. |
| CASTILLO, ANTONIO DEL. Died Oct. 28, 1895. | *JAMES, JOSEPH F. Died March 29, 1897. |
| *CUSHING, H. P. Died April 14, 1921. | JULIEN, ALEXIS A. Died May 7, 1919. |
| *DANA, JAMES D. Died April 14, 1895. | KNIGHT, WILBUR C. Died July 28, 1903. |
| DAVIS, CHARLES A. Died April 9, 1916. | LACOE, RALPH D. Died February 5, 1901. |
| DAWSON, GEORGE M. Died March 2, 1901. | LAFLAMME, J. C. K. Died July 6, 1910. |
| DAWSON, SIR J. WM. Died Nov. 19, 1899. | LAMBE, L. M. Died March 12, 1919. |
| DERBY, ORVILLE A. Died Nov. 27, 1915. | LANGTON, DANIEL W. Died June 21, 1909. |
| DRYSDALE, CHAS. W. Died July 10, 1917. | *LE CONTE, JOSEPH. Died July 6, 1901. |
| DUTTON, CLARENCE E. Died Jan. 4, 1912. | *LESLEY, J. PETER. Died June 2, 1903. |
| *DWIGHT, WM. B. Died Aug. 29, 1906. | LOUGHRIDGE, ROBT. H. Died July 1, 1917. |
| EASTMAN, CHAS. R. Died Sept. 27, 1918. | MCCALLEY, HENRY. Died Nov. 20, 1904. |
| *ELDRIDGE, GEORGE H. Died June 29, 1905. | *MCGEE, W. J. Died September 4, 1912. |
| *EMMONS, SAMUEL F. Died March 28, 1911. | MARCY, OLIVER. Died March 19, 1899. |
| FONTAINE, WM. M. Died April 30, 1913. | MARSH, OTHNIEL C. Died March 18, 1899. |
| *FOOTE, ALBERT E. Died October 10, 1895. | MELL, P. H. Died October 12, 1918. |
| *FRAZER, PERSIFOR. Died April 7, 1909. | *MERRILL, FRED. J. H. Died Nov. 29, 1916. |
| *FULLER, HOMER T. Died Aug. 14, 1908. | MILLS, JAMES E. Died July 25, 1901. |

- *NASON, HENRY B. Died January 17, 1895.
 *NEFF, PETER. Died May 11, 1903.
 *NEWBERRY, JOHN S. Died Dec. 7, 1892.
 NILES, WILLIAM H. Died Sept. 12, 1910.
 *ORTON, EDWARD. Died October 16, 1899.
 *OSBORN, AMOS O. Died March, 1911.
 *OWEN, RICHARD. Died March 24, 1890.
 PENFIELD, SAMUEL L. Died Aug. 14, 1906.
 PENHALLOW, DAVID P. Died Oct. 20, 1910.
 PIRSSON, L. V. Died Dec. 8, 1919.
 *PLATT, FRANKLIN. Died July 24, 1900.
 PETTEE, WILLIAM H. Died May 26, 1904.
 *POWELL, JOHN W. Died Sept. 23, 1902.
 *PROSSER, CHAS. S. Died Sept. 11, 1916.
 PURDUE, A. H. Died Dec. 12, 1917.
 ROGERS, G. S. Died Nov. 18, 1919.
 *RUSSELL, ISRAEL C. Died May 1, 1906.
 *SAFFORD, JAMES M. Died July 3, 1907.
 *SALISBURY, R. D. Died Aug. 15, 1922.
 *SCHAEFFER, CHARLES. Died Nov. 23, 1903.
 SEELY, H. M. Died May 4, 1917.
 SEÑA, J. C. DA COSTA. Died June 20, 1919.
 *SHALER, NATHANIEL S. Died Apr. 10, 1906.
 *SPENCER, J. W. Died July, 1921.
 SAINT JOHN, O. H. Died July 17, 1921.
 SUTTON, WILLIAM J. Died May 9, 1915.
 TARR, RALPH S. Died March 21, 1912.
 TIGHT, WILLIAM G. Died Jan. 15, 1910.
 *TODD, JAMES E. Died Oct. 29, 1922.
 *VAN HISE, C. R. Died Nov. 19, 1918.
 *VOGDES, ANTHONY W. Died Feb. 8, 1923.
 WACHSMUTH, CHAS. Died Feb. 7, 1896.
 WADSWORTH, M. E. Died April 21, 1921.
 WESTON, THOMAS C. Died July 20, 1910.
 WHITE, THEODORE G. Died July 7, 1901.
 *WHITFIELD, ROBT. P. Died April 6, 1910.
 *WILLIAMS, GEORGE H. Died July 12, 1894.
 *WILLIAMS, J. FRANCIS. Died Nov. 9, 1891.
 *WILLIAMS, H. S. Died July 31, 1918.
 WILMOTT, ARTHUR B. Died May 8, 1914.
 *WINCHELL, ALEX. Died Feb. 19, 1891.
 *WINCHELL, NEWTON H. Died May 1, 1914.
 WRIGHT, ALBERT A. Died April 2, 1905.
 *WRIGHT, G. F. Died April 20, 1921.
 YEATES, WILLIAM S. Died Feb. 19, 1908.

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PROCEEDINGS OF THE TWENTY-FIRST ANNUAL MEETING
OF THE CORDILLERAN SECTION OF THE GEOLOGICAL
SOCIETY OF AMERICA, HELD AT STANFORD UNIVER-
SITY, CALIFORNIA, APRIL 29, 1922.

AUSTIN F. ROGERS, *Secretary*

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SESSION OF APRIL 29

The twenty-first annual meeting of the Cordilleran Section of the Geological Society of America was held in conjunction with the Pacific Coast Branch of the Paleontological Society of America and the Le Conte Club, at Stanford University, on April 29, 1922.

LIST OF OFFICERS FOR 1922

President, GEORGE D. LOUDERBACK

Secretary, AUSTIN F. ROGERS

Councilor, CYRUS F. TOLMAN

PROGRAM OF PAPERS

The meeting was called to order at 10.40 a. m. by the President.

After an informal talk on a skull recently found in the gravel of the San Francisquito Creek by Bailey Willis and D. B. Seymour, the following papers were presented in the order indicated:

MIOCENE AGE OF THE OIL SHALES AT ELKO, NEVADA

BY JOHN P. BUWALDA

Paper read from manuscript and illustrated by lantern slides. Discussion by Messrs. Tolman, Lawson, Turner, and Louderback.

FAUNA OF THE SOOKE FORMATION

BY B. L. CLARK AND RALPH ARNOLD

Presented extemporaneously by Mr. Clark.

BOREAL MARINE FAUNA FROM THE UPPER OLIGOCENE OR LOWER MIOCENE OF ALASKA

BY B. L. CLARK

Presented extemporaneously. The last two papers were discussed by Messrs. Turner, Buwalda, Willis, Tolman, Lawson, and Howe.

MYADESMA, A NEW GENUS OF PELECYPODA FROM THE MARINE OLIGOCENE OF THE WEST COAST

BY B. L. CLARK

Read by title.

EOCENE VENERICARDIA OF THE WEST COAST

BY MARCUS HANNA

Presented from notes. Discussion by Messrs. Tolman, Clark, and Turner.

PHYLOGENY OF THE GENUS AGASOMA

BY HENRY V. HOWE

Presented extemporaneously. Discussion by Messrs. Willis, Clark, and Lawson.

The meeting adjourned for lunch, to meet at 2.15 p. m. During the noon recess a visit was made to the locality on the San Francisquito Creek, near the old Stanford residence, where the skull exhibited by Dr. Willis had been found by Mr. Seymour, a student at Stanford University.

The afternoon session was called to order by the President at 2.30 p. m.

VERDE RIVER LAKE BEDS NEAR CLARKDALE, ARIZONA

BY OLAF P. JENKINS

Read by title.

PREDICTION OF EARTHQUAKES

BY A. C. LAWSON

Paper read from manuscript. Discussion by Messrs. Willis, Brown, Townley, Louderback, and Tolman.

*PLEISTOCENE VERTEBRATES FROM AN ASPHALT DEPOSIT NEAR
MC KITTRICK, CALIFORNIA*

BY JOHN C. MERRIAM AND C. STOCK

Paper presented by Mr. Stock. Discussion by Messrs. Tolman, Brown, Buwalda, Louderback, and Taff.

ROCK FLOORS IN ARID REGIONS

BY AUGUSTUS LOCKE

Read by title.

GEOLOGICAL SKETCH OF THE TSIN-LING-SHAN, CHINA

BY R. R. MORSE

Illustrated by lantern slides. Discussion by Mr. Willis.

MOROCOCHA MINING DISTRICT

BY M. G. EDWARDS

Presented extemporaneously as a substitute for the paper on "Chromite-bearing dunite from Siskiyou County, California," which was to have been given by Austin F. Rogers. Discussion by Messrs. Tolman and Louderback.

GEOLOGY OF THE ALAMO MINING DISTRICT, BAJA CALIFORNIA, MEXICO

BY C. F. TOLMAN

Presented extemporaneously. Discussion by Messrs. Turner, Rogers, and Manson.

POSSIBLE CONTINENTAL LINKS

BY BAILEY WILLIS

Presented extemporaneously. Discussion by Messrs. Turner, Brown, Louderback, and Tolman.

APPOINTMENT OF NOMINATING COMMITTEE

It was moved (by Willis) and seconded (by Buwalda) that the chairman appoint a Nominating Committee to send out a ballot after the meeting. Motion carried. The following Nominating Committee was appointed: Messrs. Lawson and Tolman.

The meeting adjourned at 6.15 p. m.

ANNUAL DINNER

The Le Conte Club dinner was held in the Stanford Union.

REGISTER OF THE STANFORD MEETING, 1922

FELLOWS

J. P. BUWALDA	W. S. T. SMITH
B. L. CLARK	J. A. TAFF
A. C. LAWSON	C. F. TOLMAN
G. D. LOUDERBACK	H. W. TURNER
A. F. ROGERS	B. WILLIS

The following visitors were in attendance:

S. F. ADAMS	R. R. MORSE
C. W. BROWN	R. N. NELSON
M. G. EDWARDS	G. NORK
L. A. FAUSTINO	MRS. OLDROYD
E. L. FURLONG	W. H. SHOCKLEY
S. H. GESTER	J. P. SMITH
M. A. HANNA	C. STOCK
H. V. HOWE	H. D. SUTLIFF
C. D. HULM	A. W. THOMAS
M. C. ISRAELSKY	F. G. TICKELL
P. F. KERR	S. D. TOWNLEY
J. B. LEISER	D. T. TRASK
R. P. McLAUGHLIN	—— VORBE
M. MANSON	—— WALTER
P. P. MILLER	A. V. WOODFORD

PROCEEDINGS OF THE FOURTEENTH ANNUAL MEETING
OF THE PALEONTOLOGICAL SOCIETY, HELD AT ANN
ARBOR, MICHIGAN, DECEMBER 28-30, 1922.

R. S. BASSLER, *Secretary*

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SESSION OF THURSDAY, DECEMBER 28

The first session of the Society, announced for 2 p. m. Thursday, December 28, was postponed until Friday morning, so that the members could attend the symposium on "The Structure and History of Mountains and the Causes of their Development," commencing at that time in the meeting of the Geological Society of America. The closing hour of the morning was devoted to the address of Charles Schuchert, Fellow of the Paleontological Society and retiring President of the Geological Society of America. Professor Schuchert's address, which was introductory to the symposium, was entitled "Sites and nature of the North American geosynclines."

Thursday evening the members met with the Geological Society of

America and other affiliated societies in the complimentary smoker tendered by the University of Michigan at the Michigan Union.

SESSION OF FRIDAY, DECEMBER 29

President Matthew called the Society to order in its fourteenth annual meeting, at 9.30 a. m., in the Science Building of the University of Michigan. After welcoming the members, the report of the Council was read.

REPORT OF THE COUNCIL

To the Paleontological Society, in fourteenth annual meeting assembled:

The Council has held its customary meetings just before and after the annual meeting of the Society and has transacted other business by correspondence. A résumé of the administration of the Society's business during the fourteenth year is given below.

SECRETARY'S REPORT

To the Council of the Paleontological Society:

The Secretary's report for the year ending December 27, 1922, is as follows:

Meetings.—The proceedings of the thirteenth annual meeting of the Paleontological Society, held at Amherst, Massachusetts, December 28-30, 1921, have been printed in volume 33, number 1, of the Bulletin of the Geological Society of America, pages 191-222.

The Council's proposed nominations for officers and the announcement that the fourteenth annual meeting would be held at Ann Arbor, Michigan, December 28-30, 1921, as the guest of the University of Michigan, was issued March 22, 1922.

Membership.—The Society has been fortunate in having no loss of membership during the year. Five new members have just been elected and eight additional nominations are awaiting consideration at the present meeting. This year two of our members have been elected to fellowship in the Geological Society of America and four Fellows of that Society have asked for election to our own. The result of these various changes leaves a total number of members at the end of 1922 of 228.

Publications.—In addition to the Proceedings, four papers by members have been published in the Bulletin of the Geological Society of America.

Respectfully submitted,

R. S. BASSLER,

Secretary.

WASHINGTON, D. C., December 26, 1922.

TREASURER'S REPORT

To the Council of the Paleontological Society:

The Treasurer begs to submit the following report of the finances of the Society for the fiscal year ending December 23, 1922:

RECEIPTS

Cash on hand December 24, 1921.....	\$672.27
Membership fees.....	297.30
Interest, Connecticut Savings Bank.....	24.46
	\$994.03

EXPENDITURES

Secretary's office:

Secretary's allowance.....	\$50.00
Clerical work.....	25.00
Office expenses.....	59.30
	\$134.30

Treasurer's office:

Treasurer's allowance.....	\$25.00
Postage	3.00
	28.00

Geological Society of America:

Printing programs, etcetera.....	\$3.45
Reprints	26.06
	29.51
	191.81

Balance on hand December 23, 1922.....	\$802.22
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Net increase in funds.....	\$129.95
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Outstanding dues (1921, 1; 1922, 11).....	36.00
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Respectfully submitted,

RICHARD S. LULL,
Treasurer.

NEW HAVEN, CONNECTICUT, *December 23, 1922.*

APPOINTMENT OF AUDITING COMMITTEE

A committee consisting of W. H. Twenhofel and F. B. Loomis was then appointed by the President to audit the Treasurer's accounts.

ELECTION OF OFFICERS AND MEMBERS

President Matthew then announced the results of the ballots for the election of officers for 1923 and of new members.

OFFICERS FOR 1923

President:

T. WAYLAND VAUGHAN, Washington, D. C.

First Vice-President:

W. A. PARKS, Toronto, Ontario

Second Vice-President:

W. H. TWENHOFEL, Madison, Wis.

Third Vice-President:

O. P. HAY, Washington, D. C.

Secretary:

R. S. BASSLER, Washington, D. C.

Treasurer:

RICHARD S. LULL, New Haven Conn.

Editor:

WALTER GRANGER, New York City

NEW MEMBERS FOR 1923

JOSIAH BRIDGE, Missouri School of Mines and Metallurgy, Rolla, Missouri.

JENNIE DORIS DART, 114 High Street, New Haven, Connecticut.

GEORGE M. EHLERS, University of Michigan, Ann Arbor, Michigan.

HANDEL T. MARTIN, University of Kansas, Lawrence, Kansas.

GEORGE B. TWITCHELL, 845 Dayton Street, Cincinnati, Ohio.

The President then called for the following nominations to membership which had arrived too late for insertion on the printed ballot and which had received the approval of the Council:

HENRY G. CLINTON, Superintendent of Black Mammoth Consolidated Mining Company, Manhattan, Nevada. Student of invertebrate paleontology. Proposed by E. O. Ulrich and R. S. Bassler.

EDWARD J. FOYLES, American Museum of Natural History, New York City. Student of invertebrate paleontology. Proposed by Ralph W. Chaney and R. S. Bassler.

HEDWIG T. KNIKER, The Texas Company Building, Houston, Texas. M. A., University of Texas, 1917. Proposed by Julia A. Gardner and R. S. Bassler.

MRS. HELEN MORNINGSTAR LAMBORN, Department of Geology, Ohio State University. Ph. D. (1921), Bryn Mawr. Proposed by R. S. Lull and R. S. Bassler.

JOSEPH K. ROBERTS, Assistant Professor of Geology, Vanderbilt University, Nashville, Tennessee. Ph. D., Johns Hopkins University, 1922. Proposed by E. W. Berry and R. S. Bassler.

RICHARD W. SMITH, Assistant Geologist, State Geological Survey, Nashville, Tennessee. B. S., Massachusetts Institute of Technology, 1921. Proposed by E. O. Ulrich and R. S. Bassler.

WALTER C. TOEPELMAN, Assistant Professor of Geology, University of Colorado, Boulder, Colorado. A. B., University of Oklahoma, 1916. Proposed by Junius Henderson and R. S. Bassler.

PERCIVAL S. WARREN, University of Alberta, Edmonton, Alberta. B. A., University of Toronto, 1920. Proposed by W. A. Parks and R. S. Bassler.

After the qualifications for membership of each one of the above list had been presented to the Society, it was moved by Dr. Clarke and seconded by Professor Twenhofel that the By-Laws be suspended and that the Secretary be instructed to cast the vote of the Society for the election of these eight new nominations. Motion carried.

ELECTION OF REPRESENTATIVE ON NATIONAL RESEARCH COUNCIL

Dr. Matthew then announced that the election of a representative of the Society in the Division of Geology and Geography of the National Research Council was necessary, as Dr. Vaughan, having just completed three years of service in this position, was ineligible for reelection.

Upon vote by the Society, after motion by Professor Twenhofel, Dr. F. H. Knowlton was elected to this position.

NEW BUSINESS

The Secretary announced that J. E. Carman and John L. Tilton, both Fellows of the Geological Society of America, wished to be enrolled in the membership of the Paleontological Society, and that J. W. Gidley and Stanley Smith, just elected to fellowship in the former Society, should also be placed on our rolls. Upon motion, it was voted that the Society should add these four names to our membership.

Dr. John M. Clarke moved that, in view of the surplus in the funds of the Society, the Secretary's allowance be increased to \$100. Motion carried. There being no further business, the reading of papers was commenced in general session, with President Matthew in the chair.

PRESENTATION OF PAPERS

The first four papers of the program, all illustrated by lantern slides, were combined into a single presentation by the author. Discussion by Messrs. Parks, Loomis, Matthew, and Troxell followed.

THE BURTON DICTYOSPONGE

BY JOHN M. CLARKE

(Abstract)

This is a hexactinellid, or glass sponge, from a Chemung (Devonian) formation at Ripley, Chautauqua County, New York. The specimen described is of great size; represents, it is believed, the apertural portion of the individual, and, on the basis of other known specimens, it has been restored, the restoration and original specimen both being in the New York State Museum. The restoration gives a length of somewhat more than 10 feet. The sponge belongs to the genus *Ceratodictya* and is probably identical with the species of the Chemung formation, *C. carpenteriana* Hall and Clarke. The original specimen was found by Mrs. H. P. Burton in her 103d year.

RESTORATION OF THE COHOES MASTODON

BY JOHN M. CLARKE

(Abstract)

The Cohoes mastodon was found in a glacial pothole in the Mohawk River at Cohoes, New York, in 1865 and its skeleton is in the New York State Museum. A careful restoration of this has been made by the most careful and exact procedures and constitutes the only known attempt to represent the animal in its living state. The restoration was made by Noah T. Clarke and Charles P. Heidenrich.

PYORRHŒA IN THE COHOES MASTODON

BY JOHN M. CLARKE

(Abstract)

This skeleton has pathological dentition and erupted but one tooth on the left ramus of the mandible. This tooth has an abnormal insertion and a very imperfect opposition with the upper molars. As a result, the face of the animal is deformed and an osseous lump developed on the proximal surface of the mandible. An examination of the tooth and its socket by skillful dentists seems to have demonstrated the existence of long-continued pyorrhœal conditions, with attendant bone necrosis.

TEMPLE HILL MASTODON

BY JOHN M. CLARKE

(Abstract)

This skeleton was exhumed in 1921 from a truck garden near Temple Hill, about four miles west of Newburgh, Orange County, New York. Except for the Warren mastodon, the skeleton of which was found not far away, the new skeleton is the most complete known, the missing bones being largely a portion of the ribs and the upper surface of the cranium, which was destroyed by the

plow of the farmer. A notable feature of the skeleton is the evident incurvature and overlap of the tusks at their extremities, which are beveled, one above and one below, in such a manner as to demonstrate that the tusks formed an entire circle about the trunk.

Some of the results of the explorations of the American Museum of Natural History in China were presented by President Matthew in the following paper:

PLIOCENE MAMMALS OF SOUTHERN CHINA

BY W. D. MATTHEW AND WALTER GRANGER

(Abstract)

A large collection of skulls, jaws, and bones of fossil mammals was obtained by Mr. Granger in the winter of 1921-22 from a locality near Wan-hsien, in the province of Sze-chuan. The fauna is of late Pliocene or Pleistocene age, apparently a forest facies. Principal mammals are *Stegodon*, a rhinoceros near *R. indicus*, a giant tapir, a species of gaur (*Bibos*), several antelopes and large and small Cervidae, a pig, a tiger, *Hyæna*, *Aeluropus*, *Helarctos*, *Cyon*, *Arctonyx*, *Viverra*, a large bamboo-rat, a rabbit, a large macaque, and a new primate, probably allied to the gibbon. A single molar represents the Chalicotheres.

In view of the recent activity in work upon the Mississippian formations of the Mississippi Valley, the next paper presented by the author was of particular interest. Discussion by Messrs. Ulrich, Thomas, and Bassler.

*EARLY MISSISSIPPIAN FORMATIONS OF THE TYPE REGION ALONG
MISSISSIPPI RIVER, IN IOWA, ILLINOIS, AND MISSOURI*

BY RAYMOND C. MOORE

(Abstract)

Stratigraphic and faunal studies of the early Mississippian Kinderhook group along Mississippi River and in its vicinity, in southeastern Iowa, western Illinois, and northeastern Missouri, are the basis for a partial redefinition of the group and for the establishment of more definite correlation between exposures.

The carefully studied section at Burlington, Iowa, which is typical of deposits in a faunal province of northern affinities, is believed to include stratigraphic equivalents of the formations at Kinderhook, Illinois, and in Missouri, the latter representing lithologic and faunal developments which in the main are not observed to the north. It appears that the deposits of earliest Mississippian time in this region are marked by somewhat unusual local variations in the character of the sediments laid down and in the distribution of the invertebrate faunas. In the lowermost stratigraphic divisions which are here regarded as Mississippian there is a prominent faunal element suggestive of

the Upper Devonian, but there is a progressive and rapid increase in those forms which may be regarded as distinctively Mississippian. In general, the Kinderhook is not separated from the overlying Osage formations by an erosion interval, but the inauguration of a new stratigraphic division is indicated by a more or less marked change in lithology and, more importantly, by the introduction of faunas which are widely distributed and which in their cosmopolitan character contrast strongly with the very provincial Kinderhook faunal units.

Results of field-work in paleobotany and stratigraphy carried on during the summer of 1922 under the auspices of the Carnegie Institution were outlined by the author of the following paper:

PALEOBOTANICAL CONTRIBUTIONS TO THE STRATIGRAPHY OF CENTRAL OREGON

BY RALPH W. CHANEY

(*Abstract*)

The Crooked River occupies an area 30 to 50 miles south of the John Day Basin, in central Oregon. A comparison of the Crooked River section as exposed between Prineville and Paulina with that of the John Day Basin indicates that the sequence of the formations is practically identical. The Crooked River section shows several hundred feet of the Clarno formation with a characteristic Lower Clarno flora, and up to 4,000 feet of the John Day series, which carries near its base a flora similar to that of the Bridge Creek locality in the John Day Basin. The lavas overlying resemble the Columbia River lavas. A notable feature is the presence of dikes, which extend for over twenty miles and appear to connect with the lava flows. The formations overlying the basalt have yielded no fossils as yet, but they show a close lithologic similarity to the Mascall and Rattlesnake formations, which are the topmost members of the section in the John Day Basin to the north.

The flora of the John Day series includes over 25 species, most of which are present at the Bridge Creek locality of the John Day Basin. Live oaks, birch, poplar, elm, maple, sycamore, ironwood, and sequoia are among the more common forms. In the main these comprise a typical floodplain assemblage; the oaks and poplars suggest ridges on whose dry slopes such xerophytic types now live. A relatively high relief is also indicated by the local abundance of sequoia, suggesting that during the Oligocene, as today, this moisture-requiring form was limited to protected areas on the leeward sides of elevations. The temperature and rainfall, as indicated by the flora, suggest a climate like that in the north central United States. The recurrence of an identical flora in several horizons may indicate the destruction of the earlier forests during epochs of volcanic activity and their gradual development during the favorable conditions of intervulcanic epochs.

At 12.30 p. m. the meeting adjourned to the Michigan Union, where a complimentary luncheon was served to the members of the various scientific societies in attendance.

PRESIDENTIAL ADDRESS

At 2.30 p. m. the members convened to hear the address of Dr. W. D. Matthew, retiring President of the Paleontological Society, entitled

RECENT PROGRESS AND TRENDS IN VERTEBRATE PALEONTOLOGY

PRESIDENTIAL ADDRESS BY W. D. MATTHEW

Following the presidential address, the reading of papers in general session, with Dr. Matthew in the chair, was resumed. An account by the author of new helmet-crested dinosaurs from Alberta, illustrated by lantern slides, proved most interesting to all the members.

NEW SPECIES OF CRESTED TRACHODONT DINOSAUR

BY W. A. PARKS

(Abstract)

The genus *Stephanosaurus* was established by Lambe for the reception of a peculiar helmet-crested dinosaur from Alberta. Brown founded the genus *Corythosaurus* for another type with more pronounced helmet-like crest.

The expeditions of the University of Toronto into the bad lands of the Red Deer River, Alberta, resulted in the discovery of two heads and parts of one body of a related form distinctly intermediate between *Stephanosaurus* and *Corythosaurus*. The new species is described as *Stephanosaurus intermedius* and the opinion is expressed that the three species should be included in the one genus, *Stephanosaurus*. A rather interesting question in priority is involved.

The following paper on the paleontology and correlation of the various formations of the Richmond group, given by the author, brought forth considerable discussion, in which Messrs. Foerste, Parks, Ulrich, Ami, Bassler, and Sardeson took part.

SOME FAUNAL CORRELATIONS OF THE RICHMOND

BY W. H. SHIDELER

(Abstract)

The "Maquoketa" faunas of northeastern Illinois, eastern Wisconsin, and the upper peninsula of Michigan are well represented in Indiana, where they are found in strata of the Elkhorn beds.

These "Maquoketa" faunas constitute a fairly complete recurrence of the Fernvale fauna, but have essentially nothing in common with the typical Maquoketa of Iowa, Minnesota, and northwestern Illinois.

The typical Maquoketa was deposited in an embayment which apparently never had direct communication with the provinces to the east, and most of it is probably younger than anything in the Cincinnati region.

A paper on the correlation of Mohawkian formations in Tennessee and Kentucky was then presented by the author, who, in outlining the scope of his remarks, asked the members to delay judgment upon a recent publication on the same subject until further facts had been printed. The author then presented many valid reasons for this request.

*RELATIONS AND OVERLAPS OF ORDOVICIAN FORMATIONS IN KENTUCKY
AND TENNESSEE*

BY E. O. ULRICH

President Matthew then, in the few minutes remaining of the afternoon session, presented a digest of the following paper:

*STRATIGRAPHY OF THE SNAKE CREEK FOSSIL QUARRIES AND THE
CORRELATION OF THE FAUNAS*

BY W. D. MATTHEW

(Abstract)

The Snake Creek fossil quarries, 20 miles south of Agate, Sioux County, Nebraska, were discovered by H. J. Cook and the writer in 1908. They have yielded a great quantity and variety of vertebrates of later Tertiary age, mostly fragmentary, but including a considerable number of skulls and more or less complete skeletons. Mammals, and especially three-toed horses, are the most abundant.

Field observations and study of the collections indicate that three distinct faunas are represented and a fourth less clearly distinguishable, as follows:

- | | |
|--|-------------------------------|
| ? 4. <i>Pliohippus leidyianus</i> zone (doubtful): | } Lower |
| 3. <i>Hipparion affine</i> zone: | } Pliocene. |
| 2. <i>Merychippus paniensis</i> zone: | Late Middle or Upper Miocene. |
| 1. <i>Merychippus primus</i> zone: | Early Middle Miocene. |

The pockets from which the great bulk of the material has come are channel-beds excavated in and partly contemporary with fine-grained muddy sandstones, to which the name of Sheep Creek beds was applied when first found. These appear to be back-water sediment corresponding in age to horizons 1 and 2 of the channel-bed series. No back-water facies has been recognized for the Pliocene channel-beds (No. 3). These are overlain by eolian dune-sands, which constitute the top of the formation and are considerably compacted near the old surfaces. These eolian beds contain a scanty Pliocene fauna, doubtfully separable from No. 3.

The American Museum Expedition of 1922 secured a large collection from the channel-bed facies of the *M. primus* zone.

At 5.30 p. m. the Society adjourned until the following day.

Friday evening, at 7 o'clock, at the Michigan Union, the members attended the annual dinner of the Geological Society of America and affiliated societies.

SESSION OF SATURDAY, DECEMBER 30

At 9.30 Saturday morning the Society met in general session, with President Matthew in the chair. The first paper of the program was illustrated by the recently completed geologic map of the Franklin quadrangle in central Tennessee and by lantern slides.

EMBAYMENTS AND OVERLAPS IN CENTRAL TENNESSEE

BY R. S. BASSLER

(Abstract)

On account of incomplete knowledge, paleogeographic maps can seldom be made with great accuracy. By a combination of the Columbia folio map of Hayes and Ulrich and the geological map of the adjoining Franklin quadrangle, just completed by the writer, the geology of a considerable area in central Tennessee is now available in much detail and the distribution of the formations can be plotted in the form of paleogeographic maps. Such maps show that certain formations, as the Richmond, Brassfield, and New Providence, occupy embayments in the old Nashville dome, while the Lowville, Leipers, Bigby, Cannon, and other formations show broad overlaps generally to the east or to the west, caused probably by oscillation of the area.

Convincing data as to the Richmond age of the Arnheim formation of the Ohio Valley, hitherto believed by some to belong to the Maysville group of the Ordovician, were presented in the following paper, which was discussed by various members of the Society:

THE BASAL RICHMOND OF THE CINCINNATI PROVINCE

BY W. H. SHIDELER

(Abstract)

The top of the Maysville (Mount Auburn) is everywhere, in Ohio, Indiana, and Kentucky, separated from the base of the Richmond (Arnheim) by evidences of a stratigraphic break. This appears to be due merely to a cessation of deposition, as there is nowhere in the Cincinnati province any evidence of post-Maysville and pre-Richmond erosion.

In Ohio and Indiana the fauna of the lower or Sunset subdivision of the Arnheim seems, on superficial examination, to consist of a distinct Maysville element (largely recurrent Corryville), plus a Richmond element. Upon close examination the recurrent Corryville forms are found to be mostly undescribed species. The Richmond element appears, not at the *Dinorthis carleyi* zone in the middle, but at the base. Here it appears everywhere except in the more southern exposures in Kentucky, where the strata are largely barren of fossils.

President Matthew then presented for the author an abstract of three papers dealing with problems in vertebrate paleontology, as follows:

CARNIVOROUS SAURISCHIA IN EUROPE LATER THAN THE TRIAS

BY F. VON HUENE

CONTRIBUTION TO THE VOMER-PARASPHENOID QUESTION

BY F. VON HUENE

*LINES OF PHYLETIC AND BIOLOGICAL DEVELOPMENT OF THE
ICHTHYOPTERYGIA*

BY F. VON HUENE

A paper on the fauna found in the sandstone making the rim of Goshen Hole, Wyoming, showing its relation to the Leptauchenia beds elsewhere was given by the next speaker and a spirited discussion of the subject followed.

MIOCENE BEDS ABOUT GOSHEN HOLE, WYOMING

BY F. B. LOOMIS

A preliminary notice concerning some ostracoderm remains found in shale associated with the Monroe formation in Ohio was the subject of the next paper, in which the author pointed out clearly and illustrated by lantern slides the relation of the material to the described genera of ostracoderms of America and Great Britain and discussed the stratigraphy of the occurrence. Further discussion by Messrs. Tilton and Bassler.

PRELIMINARY REPORT CONCERNING SOME NEW OSTRACODERMS FROM OHIO

BY J. E. CARMAN

An explanation of the origin of the many growth layers found in such fossil organisms as stromatoporoids, bryozoa, and certain corals was suggested in the next paper, which was illustrated by lantern slides.

THE PROBLEM OF FOSSIL MULTILAMELLAR INVERTEBRATES

BY R. S. BASSLER

(Abstract)

In the course of studies upon Cretaceous multilamellar cyclostomatous bryozoa by F. Canu and the writer, it was discovered that the various superposed lamellæ originated in certain tubes which proceeded unchanged from the preceding lamella and which by their proliferation gave rise to all the surrounding cells of the same layer of zooecia. These generative tubes occur at stated intervals and mark off the surface in more or less regular areas of growth. It is suggested that the monticules and maculæ of Paleozoic bryozoa

originated in some such way and that other multilamellar organisms owe their growth to similar methods.

An account of American rhinoceroses and the evolution of one genus, well illustrated by lantern slides, was next presented by the author. Discussion by Messrs. Loomis and Matthew.

AMERICAN RHINOCEROSES AND THE EVOLUTION OF DICERATHERIUM

BY E. S. TROXELL

(Abstract)

Scarcely any animal seems more exotic to America than does the rhinoceros. Limited at present to Asia and Africa, we have every reason to believe that they originated in America. In our own continent we can trace the line or lines of descent from *Hyrachyus* and allied forms of the middle Eocene through to the Pliocene, where the family becomes extinct. Horns were developed in the early Miocene, but their incipient beginning is noted in the Eocene. *Dicera-therium*, the "two-horned beast" described by Marsh, is clearly related to *Canopus*, and by gradual steps its change from that genus can be traced until it reached its splendid development in the late Oligocene. This alone offers convincing proof of the law of evolution.

The following papers were then read by title:

PRESENT STATUS OF THE OZARKIAN AND CANADIAN SYSTEMS

BY E. O. ULRICH

MARINE EOCENE HORIZONS OF WESTERN NORTH AMERICA

BY BRUCE CLARK

SOOKE FORMATION OF SOUTHERN VANCOUVER ISLAND

BY BRUCE CLARK AND RALPH ARNOLD

EVOLUTION OF *STROPHEODONTA DEMISSA* (CONRAD) IN THE SNYDER CREEK SHALES OF MISSOURI

BY E. B. BRANSON AND JAMES S. WILLIAMS

(Abstract)

The evolution discussed in this paper took place while 30 feet of shales were being deposited. At the base of the Snyder Creek shales *Stropheodonta demissa* (Conrad) showed variational tendencies in the following directions: toward long hingeline and short hingeline; thick shell and thin shell; great convexity and flatness; fine plications and coarse plications; strongly projecting umbo and retreating umbo; narrowness and great width; well developed fold and sinus.

The following species evolved: *S. callawayensis* Swallow: Shell thick, coarsely plicate, hinge longer than greatest width of shell. *S. boonensis* Swallow: Shell thick, coarsely plicate, strongly convex. *S. equicostata* Swallow: Shell thin, hinge shorter than greatest width of shell, finely plicate. *S. cymbiformis* Swallow: Shell thin, hingeline very short, finely plicate, umbo projecting prominently behind hingeline. *S. inflexa* Swallow: Shell thick, hingeline shorter than greatest width of shell, umbo projecting prominently behind hingeline. *S. navalis* Swallow: Shell thick, coarsely plicate, very convex, imperfectly developed carinate fold.

The University of Missouri has more than 2,000 specimens of Snyder Creek stropheodonts and series have been arranged showing minute variations from *S. demissa* (Conrad) to each of the species listed above. The intermediate grades are rare, while there are large numbers of the typical forms.

All of the new species disappeared before 50 feet of Snyder Creek shales had been deposited.

The Society then adjourned.

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CORRESPONDENTS DECEASED

KOKEN, E. Died Nov. 24, 1912. WOODWARD, DR. H. Died Sept. 6, 1921.
 NATHORST, DR. A. C. Died Jan. 20, 1921.

MEMBERS DECEASED

BARRELL, JOSEPH. Died May 4, 1919.	HAMLIN, HOMER. Died in July, 1920.
BILLINGS, W. R. Died March 1, 1920.	HARPER, GEORGE W. Died Aug. 19, 1918.
CALVIN, SAMUEL. Died April 17, 1911.	HAWVER, J. C. Died May 15, 1914.
CLARK, WM. B. Died July 27, 1917.	LAMBE, L. M. Died March 12, 1919.
CROZEL, GEORGES. Died Oct., 1921.	LYON, VICTOR W. Died Aug. 17, 1919.
DERBY, ORVILLE A. Died Nov. 27, 1915.	MOODY, W. L. Died Oct. 9, 1920.
DONEGHY, JOHN T. Died June 29, 1921.	PROSSER, C. S. Died Sept. 11, 1916.
EASTMAN, CHAS. R. Died Sept. 27, 1918.	SEELY, HENRY M. Died May 4, 1917.
FONTAINE, WM. M. Died April 30, 1913.	WARING, CLARENCE A. Died Nov. 4, 1918.
GILL, THEODORE N. Died Sept. 25, 1914.	WILLIAMS, HENRY S. Died July 31, 1918.
GORDON, ROBERT H. Died May 10, 1910.	WILLISTON, S. W. Died Aug. 30, 1918.

PROCEEDINGS OF THE SECOND ANNUAL MEETING OF THE
SOCIETY OF ECONOMIC GEOLOGISTS, HELD AT ANN
ARBOR, MICHIGAN, DECEMBER 28-30, 1922.

SYDNEY H. BALL, *Secretary*

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SESSION OF THURSDAY, DECEMBER 28

The second annual meeting of the Society of Economic Geologists was held at Ann Arbor, Michigan, December 28-30, 1922, simultaneously with the meetings of the Geological Society of America.

SESSION OF FRIDAY, DECEMBER 29

The session of Friday was called to order by President Waldemar Lindgren.

ELECTION OF OFFICERS FOR 1923

The election of officers for 1923 was declared to have resulted as follows:

President, J. E. SPURR

Vice-President, ANDREW C. LAWSON

Councilors, 1923-1924, RALPH ARNOLD, L. C. GRATON, and
WILLET G. MILLER

PRESENTATION OF PAPERS

The following papers were presented during the meeting:

(143)

1. *THE HOMESTAKE OREBODY*

BY SIDNEY PAIGE

Discussed by Messrs. Spurr, Runner, Lindgren, and U. S. Grant.

2. *CRITERIA BY WHICH TO DETERMINE THE DIRECTION OF FAULTS*

BY BAILEY WILLIS

Discussed by Messrs. Spurr, Paige, Hotchkiss, Lindgren, and Kemp.

3. *STRUCTURAL FEATURES EXHIBITED BY THE QUARTZITES IN THE LEAD REGION, SOUTH DAKOTA*

BY J. J. RUNNER

Discussed by Messrs. Spurr, Paige, Lindgren, and U. S. Grant.

4. *GEOGRAPHIC DISTRIBUTION OF ORE DEPOSITS IN AUSTRALIA*

BY E. C. ANDREWS

Read by title.

5. *CONCENTRATION AND CIRCULATION OF THE ELEMENTS FROM THE STANDPOINT OF ECONOMIC GEOLOGY*

PRESIDENTIAL ADDRESS BY WALDEMAR LINDGREN

6. *NATIVE COPPER DEPOSITS OF MICHIGAN*¹

BY L. C. GRATON

Discussed by Messrs. Graton, Kemp, Seaman, Leith, Lane (read extract of his report, read extract of Jaggar, and spoke), Lawson, Leith, Grout, Leith, Bateman, Lewis, Butler (in rebuttal), Wells, Hotchkiss, Bayley, Butler, Wright, Bayley, Wright, Lane, and Graton.

7. *SOLVENTS AND PRECIPITANTS OF METALLIC COPPER*

BY ALFRED C. LANE²

Discussions same as number 6.

8. *CHEMICAL SUGGESTIONS CONCERNING THE ORIGIN OF LAKE SUPERIOR COPPER ORES*

BY R. C. WELLS³

Discussions same as number 6.

¹ Presented by courtesy of Geological Department, Calumet and Hecla Mining Company.

² Introduced by B. S. Butler.

³ Introduced by B. S. Butler.

9. *SOME CONSIDERATIONS RELATING TO THE ORIGIN AND HISTORY OF THE
LAKE SUPERIOR SYNCLINE*

BY W. O. HOTCHKISS

Discussions same as number 6.

10. *MAGNETIC SURVEYING ON THE COPPER-BEARING ROCKS OF WISCONSIN*

BY HENRY R. ALDRICH ⁴

Discussions same as number 6.

11. *NATIVE COPPER DEPOSITS OF THE SOUTHERN ATLANTIC STATES AS
COMPARED ESPECIALLY WITH THOSE OF MICHIGAN*

BY THOMAS L. WATSON.

Read by title.

12. *GENETIC COMPARISON OF THE MICHIGAN AND BOLIVIAN COPPER
DEPOSITS*

BY JOSEPH T. SINGEWALD, JR.

Read by E. B. Mathews.

13. *SIMILARITIES AND CONTRASTS BETWEEN NATIVE COPPER DEPOSITS OF
NEW JERSEY AND OF MICHIGAN*

BY J. VOLNEY LEWIS

Discussions same as number 6.

SESSION OF SATURDAY, DECEMBER 30

PRESENTATION OF PAPERS

14. *MOTHER PLANTS OF PETROLEUM*

BY DAVID WHITE

15. *CORRELATION OF OIL-BEARING ROCKS IN COLORADO AND WYOMING*

BY WILLIS T. LEE

16. *CAPILLARY RELATIONS OF OIL AND WATER*

BY C. W. COOK

Discussed by O. E. Meinzer.

⁴ Introduced by W. O. Hotchkiss.

17. *ROAD MATERIALS INVESTIGATION IN WISCONSIN*

BY E. F. BEAN

Discussed by W. A. Nelson.

18. *SUGGESTED EXPLANATION OF THE HIGH FERRIC IRON CONTENT OF LIMESTONE CONTACT ZONES*

BY B. S. BUTLER

19. *AN EFFECT OF CLIMATIC CHANGE ON THE SUPERFICIAL ALTERATION OF ORE DEPOSITS*

BY HENRY H. KNOX

Read by title.

20. *TITANIFEROUS IRON ORES OF WESTERN NORTH CAROLINA*

BY W. S. BAYLEY

Discussed by H. S. Washington.

21. *PRIMARY CHALCOCITE, BRISTOL COPPER MINE, CONNECTICUT*

BY ALAN M. BATEMAN

Discussed by Messrs. Lewis and Graton.

22. *A SOURCE OF PRESSURE FOR ORE FORMATION*

BY L. C. GRATON

Discussed by Messrs. Lawson, Bowen, Wright, Larsen, and Spurr.

23. *MAGNETITE PEGMATITES IN NORTHERN MINNESOTA*

BY FRANK F. GROUT

Discussed by Messrs. Miller, Wright, Lane, and Lawson.

24. *LADDER VEINS IN MINNESOTA*

BY FRANK F. GROUT

Discussed by Messrs. Miller, Wright, Lane, and Lawson.

25. *ROCK ALTERATION IN CONTACT WITH SULPHIDES AT SUDBURY, ONTARIO*BY ALFRED WANDKE AND ROBERT HOFFMAN ⁵

⁵ Introduced by L. C. Graton.

PROCEEDINGS OF THE THIRD ANNUAL MEETING OF THE
MINERALOGICAL SOCIETY OF AMERICA, HELD AT ANN
ARBOR, MICHIGAN, DECEMBER 29, 1922.

FRANK R. VAN HORN, *Secretary pro tempore*

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SESSION OF FRIDAY, DECEMBER 29

The Mineralogical Society of America held its third annual meeting at the University of Michigan, Ann Arbor, Michigan, on December 29, 1922, in affiliation with the Geological Society of America. The meeting in the Mineralogical Lecture Room was called to order at 9.30 a. m. by President Thomas L. Walker. In the absence of the retiring Secretary, Herbert P. Whitlock, it was moved, seconded, and carried that Frank R. Van Horn act as Secretary *pro tempore*.

On motion of the Secretary, the reading of the minutes of the last annual meeting was dispensed with, in view of the fact that they have been printed on pages 45-50 of volume 7, number 3, of the American Mineralogist.

ELECTION OF OFFICERS AND FELLOWS FOR 1923

The Secretary announced that 64 ballots had been cast for the officers for 1923, as nominated by the Council, and that the list was elected. It is as follows:

President, EDGAR T. WHERRY

Bureau of Chemistry, Washington, D. C.

Vice-President, GEORGE F. KUNZ

New York City

Secretary, FRANK R. VAN HORN

Case School of Applied Science, Cleveland, Ohio

Treasurer, ALBERT B. PECK

University of Michigan, Ann Arbor, Mich.

Editor, WALTER F. HUNT

University of Michigan, Ann Arbor, Mich.

Councilor, ESPER S. LARSEN

U. S. Geological Survey, Washington, D. C.

The Secretary also reported that the Council had elected the following Fellows:

ALFRED SCHOEP, Professor of Crystallography and Mineralogy, University of Ghent, Belgium.

W. L. UGLOW, Professor of Mineralogy and Petrology, University of British Columbia, Vancouver, B. C.

FRANK A. WILDER, North Holston, Virginia.

WASHINGTON A. ROEBLING, Trenton, New Jersey.

EDWARD F. HOLDEN, University of Michigan, Ann Arbor, Mich.

REPORT OF THE SECRETARY

The Secretary reported that the roll of the Society now comprises 69 Fellows and 161 members, a gain of 3 Fellows and 12 members for the year.

REPORT OF THE TREASURER

The Treasurer read his report for the year. On motion, an Auditing Committee, consisting of Dr. E. T. Wherry and Prof. A. L. Parsons, was appointed by the President. This committee, at a later session, reported that they found the books of the Treasurer correct.

REPORT OF THE EDITOR

The Editor reported an increase in the size of the *American Mineralogist* of 21.5 per cent for the year 1922. Of the 214 pages comprising

volume 7, 59.1 per cent of the space was devoted to original articles, 22.3 per cent to proceedings of societies, notes and news, and book reviews, leaving 18.3 per cent for new minerals and abstracts.

REPORT OF THE COMMITTEE ON THE NOMENCLATURE AND CLASSIFICATION
OF MINERALS

Prof. Thomas L. Watson, chairman of the committee, read a lengthy report. It was moved to issue the latter part of this report to the members of the Society for criticism and comment.

It was moved by Prof. E. H. Kraus, also seconded and carried, that the Society extend a vote of thanks to the committee for its efforts during the past two years.

GREETINGS TO PROFESSORS GROTH AND GOLDSCHMIDT

It was moved, seconded, and carried that the greetings of the Society be extended to Professors Paul Groth and Victor Goldschmidt on the approaching anniversaries of their 80th and 70th birthdays.

PRESENTATION OF PAPERS

The presentation of scientific papers was then taken up as follows, according to the program:

PROGRESS OF MINERALOGICAL METHODS

PRESIDENTIAL ADDRESS BY THOMAS L. WALKER

POSSIBLE SOURCE OF METALLIC SULPHIDES IN LIMESTONE

BY ALEXANDER H. PHILLIPS

MINERALOGRAPHY AS AN AID TO MILLING

BY ELLIS THOMSON

Read by A. L. Parsons.

FORMATION OF KAOLIN AT MODERATE DEPTHS

BY A. L. PARSONS

HISINGERITE FROM DELAWARE

BY ALFRED C. HAWKINS

CATAPELIITE FROM MAGNET COVE

BY W. F. FOSHAG

Read by E. T. Wherry.

COMPOSITION OF THOMSONITE

BY EDGAR T. WHERRY

VOLUME ISOMORPHISM IN THE SILICATES

BY EDGAR T. WHERRY

URANITE GROUP: AUTUNITE, CARNOTITE, SINCOSITE, ETCETERA

BY W. T. SCHALER

Read by Frank R. Van Horn.

*USE OF PROJECTION APPARATUS IN TEACHING CERTAIN PHASES OF
MINERALOGY*

BY EDWARD H. KRAUS

OCCURRENCE OF LEUCITE IN THE ALBAN HILLS

BY HENRY S. WASHINGTON

*CRYSTALLOGRAPHY AND OPTICAL PROPERTIES OF A URANIUM MINERAL
(SCHOEPITE), FROM THE CONGO*

BY T. L. WALKER

*ELLSWORTHITE, NEW HYDROUS URANIUM COLUMBATE FROM HYBLA,
HASTINGS COUNTY, ONTARIO*

BY T. L. WALKER AND A. L. PARSONS

VANADIUM DEPOSITS OF THE SOUTHWEST AFRICAN PROTECTORATE

BY CHARLES PALACHE

DIAMOND MINES OF SOUTH AFRICA

BY CHARLES PALACHE

THE GEOLOGICAL SOCIETY OF AMERICA

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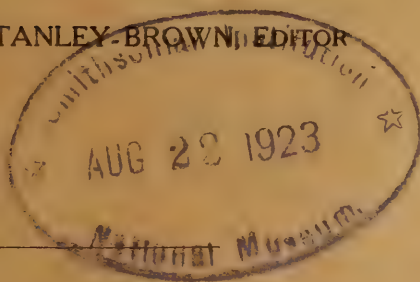
ALFRED H. BROOKS, Washington, D. C.

BULLETIN
OF THE
Geological Society of America

VOLUME 34 NUMBER 2
JUNE, 1923



JOSEPH STANLEY BROWN, EDITOR



PUBLISHED BY THE SOCIETY
MARCH, JUNE, SEPTEMBER, AND DECEMBER

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SITES AND NATURE OF THE NORTH AMERICAN
GEOSYNCLINES¹

PRESIDENTIAL ADDRESS BY CHARLES SCHUCHERT

(Read in part before the Society December 28, 1922)

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¹ Manuscript received by the Secretary of the Society April 19, 1923.

This paper is one of a series composing a "Symposium on the structure and history of mountains and the causes of their development."

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INTRODUCTION

It was in 1903 that the writer printed his first paleogeographic map, and seven years later that the Geological Society of America did him the great honor of publishing fifty-two such maps of North America. Since then, as stratigraphers have brought to light new data, today from Alaska and tomorrow, perhaps, from Mexico, these maps have been altered to record the new finds, and their number has increased until they now represent one hundred and fifteen formations, beginning with the earliest Cambrian. It is, therefore, a pleasure for the writer to bring before the same Society that fourteen years ago listened to the initial presentation of these North American maps the broader conclusions that have crystallized out of their study during the intervening years.

The synthesis of my studies may be expressed in the words of another presidential address, namely, that of Le Conte, given in 1897.² Nearly all of the processes of nature visible to us, he said, derive their forces from the sun. Currents of air and water in their eternally recurring cycles are a circulation driven by the sun. Plants derive their forces directly, and those of animals indirectly through plants, from it. To this

² Joseph Le Conte: Earth-crust movements and their causes. This Bulletin, vol. 8, pp. 113-114.

almost universal law there is but one exception, namely, the internal forces of the earth.

"Thus, then, all geological agencies are primarily divided into two groups. In the one group come atmospheric, aqueous, and organic agencies, together with all other terrestrial phenomena which constitute the material of science; in the other group, igneous agencies and their phenomena alone. The forces in the one group are exterior; in the other, interior; in the one sun-derived; in the other, earth-derived. The one forms, the other sculptures, the earth's features. . . . The general effect of the one is to increase the inequalities of the earth's surface, the other to decrease and finally to destroy them. . . . All that constitutes physical geography at any geological time is determined by the state of balance between these two eternally antagonistic forces."

It is now well established that the geologic history of the earth is cyclic in its nature, cyclic in that the periods have (1) long intermediate times when the lithosphere undergoes peneplanation and warping movements comprehended under the term *epeirogenic*, and (2) shorter closing epochs when the earth's outer shell is locally folded into mountains, the *orogenic* times. During the intermediate times, organic evolution is almost static (biostatic), but is quickened in the cooler and drier orogenic epochs. The times of lesser crustal folding occur toward the close of the periods, and when the diastrophism is world-wide, as toward the close of the eras, then the life of the earth passes through critical or revolutionary times, with quickened evolution and vanishing of the overspecialized stocks.

The cause of the cyclic changes in the surface of the earth is to be sought in the variable tensions in, and the elasticity of, the lithosphere. These are brought about by radial shrinkage, or the contraction energies. The tensions are of slow accumulation during the *epeirogenic* times, and they give way to crustal movements during the *orogenic* epochs of compensation.

RISE OF THE THEORY OF GEOSYNCLINES

GENERAL DISCUSSION

The unraveling of American geology began in earnest with the organization of the State Survey of Massachusetts in 1830, and in 1836 that of New York, the State destined to be the court of last resort in Paleozoic stratigraphy. Merrill tells us in his comprehensive "Contributions to the history of American geology" that during the decade 1830-1839 official surveys were organized by no fewer than fifteen States, and national ones carried on by Owen and Featherstonhaugh in the Mississippi Valley. During the next twenty years eleven other State surveys

came into being, besides the path-finding Federal ones of Foster and Whitney in the Lake Superior country, and the railway surveys across the Rocky Mountains of Emory, Marcy, Pope, Ives, Newberry, and Macombe. The stratigraphic results of these many and widely spread geologic and geographic efforts stand recorded chiefly in the work of Hall, Vanuxem, and Emmons in New York and elsewhere, of Hitchcock in New England, of the brothers Rogers in Pennsylvania and Virginia, of Safford in Tennessee, of Owen in the Mississippi Valley, and of Dawson and Logan in Canada.

In the matter of mountain origins, the path was blazed first by the Rogers brothers and later by James Hall, followed by James D. Dana and Joseph Le Conte. The area of their generalizations was chiefly the Appalachian Mountains, extending from Tennessee through the Virginias, Pennsylvania, New York, Vermont; thence northeast through Quebec to Gaspé. As early as 1842 the Rogers brothers offered an explanation, not only for the structure of the Appalachians, but for their causes as well, though H. D. Rogers did not see his epochal "Final Reports on Pennsylvania" published until 1858.

The pioneer theory of mountain-making which is of most interest to us at present, however, was that of James Hall, first formulated in his presidential address on the "Geological history of the North American Continent," before the American Association, at Montreal, in 1857—according to J. M. Clarke, Hall's "most notable performance in philosophical geology," having "all the exciting interest of novelty." This address had to do with the procedure of mountain-making and continental uplift. "It was a carefully thought out course of argument," continues Clarke; "but obviously Hall presented it with tentative caution and some degree of timidity—at all events, with entire absence of finality—for he would not permit its publication in the usual way in the next year's volume of the Association's proceedings."³

In the meantime Hall hinted at his ideas in the "Geology of Iowa" (1859), and set them forth more in detail in the third volume of the "Paleontology of New York," published in 1861. Even after reading this more extended account, however, one gets no such clear mental picture of Hall's theory as in the original statement of 1857, first published in 1883.⁴ Hall's views are not yet altogether clear, and it is therefore no wonder that "the geologists went away from Montreal shaking their heads," and that shortly afterward Hall was told by Dana that he had

³ J. M. Clarke: James Hall, of Albany, geologist and palæontologist, 1921, p. 325.

⁴ James Hall: Contributions to the geological history of the American continent. Proc. Amer. Assoc. Adv. Sci., vol. 31, pp. 29-69.

developed "a theory of mountains with the origin of mountains left out." To this Le Conte added that Hall left "the sediments just after the whole preparation had been made, but before the actual mountain formation has taken place."⁵

Hall's ideas of mountain origin, as we see his theory now, refer rather to mountains of sculpture, since he held that their internal structure was impressed upon them during the time of their sedimentary accumulation. "It is certainly one of the great glories of American geology to have clearly shown by the study of the Appalachian chain the immensity of the work of erosion, and that the present sculpture owes its origin to this cause alone."⁶

HALL'S THEORY OF SYNCLINES AND CRUSTAL FOLDING

Putting together all of Hall's various statements, his theory as to the making of the Appalachian Mountains is briefly as follows:

Mountains occur only in areas of greatest sedimentary accumulation, and never where formations are thin. Where the strata are thickest, there they accumulated in shallow seas, and the whole subsiding area, whether the sinking was gradual or periodic, always remained shallow. A northeastern ocean, spreading southwestward into Canada and the United States, gathered the detritals of Laurentia, and more especially of Appalachia, and laid them down along the northwestern side of the latter land, where the currents were strongest. This interior ocean, as he called it, extended westward to the Rocky Mountains. In the Appalachian seaway, he said, the Paleozoic formations are possibly ten times, and certainly six times, thicker than the equivalent deposits of the same seas in the Mississippi Valley. In consequence the area of greatest sedimentary accumulation formed a very long and comparatively narrow mass of stratified rock having eventually the general structure of a vast and very deep syncline that lay closely adjacent to an eastern land which rose periodically in compensation for the sinking syncline.

During the accumulation of the sediments in the syncline, according to Hall, the bottom strata would gradually become stretched and rent with fractures, while from time to time in the upper or younger deposits a folding movement would take place, making land areas which sooner or later were eroded to sealevel and may or may not have become buried beneath subsequent seas.

Hall distinctly stated that the folding of strata seemed to him to be

⁵ Joseph Le Conte: On the formation of the features of the earth surface. *Amer. Jour. Sci.* (3), vol. 5, 1873, p. 450.

⁶ Le Conte: *Op. cit.*, p. 451.

"a very natural and inevitable consequence of the process of subsidence." He denied "the influence of local elevating forces and the intrusion of ancient or plutonic formations beneath the line of mountains, as ordinarily understood and advocated." He goes on to say:⁷

"The sinking down of the mass produces a great synclinal axis; and within this axis, whether on a large or small scale, will be produced numerous smaller synclinal and anticlinal axes. . . . I hold, therefore, that it is impossible to have any subsidence along a certain line of the earth's crust, from the accumulation of sediments, without producing the phenomena which are observed in the Appalachian and other mountain ranges."

According to Hall, therefore, the internal structure of folded mountains was made during the accumulation of the strata in compensation for differential movements of the formations while they were sinking, and not through lateral thrusting of an eastern inwardly moving land. It further appeared to him that folding had contributed nothing to the altitude of mountains. Later on, however, the loaded and folded marine area was subjected to continental elevation in a vertical direction (epeirogenic), and the elevating was highest in the area of thickest sedimentary accumulation.

Hall did not say why the continent was vertically elevated, since his views were not a theory of mountain-making, but he held that "mountain ranges were coincident with lines of great sedimentary accumulation," and that "this accumulation of sediments, with its subsidence and consequent folding and plication and the subsequent elevation of the mass and erosion of the anticlinals, had shaped the mountains." Further, "that the mountain elevations were never equal to the vertical thickness of the strata composing them. I intended to imply that mountain elevation was due to sedimentary accumulation and subsequent continental elevation."⁸

DANA ON GEOSYNCLINES, SYNCLINORIA, AND ANTICLINORIA

It is apparent from the above that the theory of geosynclines, as we now hold it, had its inception in the idea of trough or syncline areas of sedimentation as set forth in 1857 by Hall. This was, according to Dana, "the first statement of this grand principle in orography." Then the theory lay more or less dormant until 1873, when Dana showed⁹ that the great subsidences of the globe have not been made by the gravity of ac-

⁷ Paleontology of New York, vol. 3, 1861, p. 70.

⁸ James Hall: Proc. Amer. Assoc., vol. 31, 1883, p. 68.

⁹ James D. Dana: On some results of the earth's contraction from cooling, including a discussion of the origin of mountains, and the nature of the earth's interior. Amer. Jour. Sci. (3), vol. 5, pp. 423-443; vol. 6, pp. 6-14, 104-115, 161-172.

cumulating sediments, an explanation which, he states, is "wholly at variance with physical law." It was at this time that Dana introduced the term *geosynclines* for what Hall had called synclines, because they do not have the simple synclinal structure, but are made up rather of "many true or simple synclinals as well as anticlinals." The mountain system that eventually rises out of a geosyncline, Dana at the same time called a *synclinorium*. In other words, synclinorial mountains arise subsequently, through folding due to lateral compression, out of the strata of a geosyncline.

"The term thus introduced by Dana has, unfortunately, been diverted from its original meaning and applied to a general syncline compounded of minor folds and contrasted with *anticlinorium*. It has thus become a term of structure, and the related idea of mountain-making, which the name expresses, has been relegated to a subordinate position, or entirely left out."¹⁰

"The geosynclinal ranges or synclinoria have experienced in almost all cases, since their completion, true elevation through great geanticlinal movements, but movements that embraced a wider range of crust than that concerned in the preceding geosynclinal movements—indeed, a range of crust that comes strictly under the designation of a polygenetic mass." In other words, "Mountain chains are combinations of synclinoria and of anticlinorian elevations."¹¹

Dana in 1895 says further:¹²

"The great facts to be explained in a theory of mountain-making relate (1) to the preparatory geosyncline or trough and its load of strata for the mountain structure; (2) to the mountain-making events—the upturning, flexing, and faulting of the strata, and all other effects of the movements in progress. On any theory of origin, such mountain ranges are *synclinoria*, as they have been termed by the author, from the Greek for *syncline*, and *ὄρος*, *mountain*, they having had their beginning, as first recognized by Hall, in a preparatory geosyncline of accumulation. The geosyncline occupied the area of the future mountain range."

TWO KINDS OF GEOSYNCLINES IN NORTH AMERICA

Just as there are several categories of geanticlines, so there are at least two types of geosynclines, some (1) with comparatively short and simple histories, like the Acadian and Saint Lawrence troughs, or with longer histories, like the Franklinian; and (2) others, very extensive in time and space, having undergone long and complicated evolutions, as did the Appalachian and Cordilleran (see maps, figures 1 and 3).

In America, where the theory of geosynclines arose, the idea is typified by the structure of the Appalachian-Allegheny area, and it is admitted

¹⁰ L. V. Pirsson: Text-book of geology, Pt. I, Physical geology, 2d ed., 1920, p. 306.

¹¹ Dana: Op. cit., pp. 432, 171.

¹² Dana: Manual of geology, 4th ed., p. 380.

by every one, at least tacitly, that this geosyncline has always been a part of the North American continent. In other words, the Appalachian geosyncline has never been a part of the oceans or mediterraneans, nor does it, like the mediterraneans, *lie between continents* (see page 194). Furthermore, as the loading of this geosyncline did not make it subside, it follows that there must have been another crustal element orogenetically connected with it. This was, of course, the outer, mobile, progressively rising borderland, Appalachia, which finally became a highly elevated anticlinorium, delimiting the Appalachian geosyncline on the west and shedding into it most of its sediments. The Appalachian-Allegheny Mountains are, therefore, a combined synclinorium and anticlinorium, or, as Dana would say, a "polygenetic mass."

BORDERLANDS OF NORTH AMERICA

(See Map, Figure 3)

GENERAL DISCUSSION

From the geographic position of the geosynclines near the margins of the continent, and the further fact that the main masses of their sediments came not from the medial area of the continent, but from more or less narrow lands facing the oceans, it is clear that North America was originally much more extensive than now. Since these facts are already true in Lower Cambrian time, it is also clear that the extent of greater North America was established in Proterozoic time. Even throughout the later Proterozoic we see the presence of a Cordilleran geosyncline in the same general area as the seaways of the early Paleozoic, and it follows that greater North America came into existence at least in early Proterozoic time. The present area of North America is over 8,300,000 square miles and Greenland has in addition about 850,000 square miles. In Proterozoic time, on the other hand, the writer believes that greater North America had an area of over 11,000,000 square miles; that since then Greenland has become a separate land, and that in addition some 2,000,000 square miles of the continent have been warped and fractured into the oceanic realms. These statements are portrayed on the map, figure 2.

Almost the entire outer areas of North America show in their geologic structure that a more or less wide belt has been the most mobile part of the continent. At various times these marginal lands have periodically risen into more or less high lands, and they have been the main source for the sediments of the geosynclines situated along their inner sides. On the outside of the borderlands lie the permanent oceanic basins. How

far these lands once extended beyond the present shorelines into the oceans is unknown, but it is certain that much of their outer portions have been fractured into the ocean depths. The present continental shelves are therefore held to be of fairly recent origin—of late Cretaceous making along the Atlantic and of late Cenozoic origin on the Pacific side of the continent.

The topographically more or less high borderlands of North America—the frame surrounding the inner basin—are periodically raised, and this appears to be due to a shrinking earth. The earth is continually cooling, though seemingly at an excessively slow rate, through internal magmatic differentiations; it is also losing gases and water, while the centrosphere is in molecular rearrangement, due to the great attraction pressures of the earth's mass; and because of these changes the earth shrinks in volume. The outer lithosphere, on the other hand, is stiff, rigid, and very strong, and hence long resists the shrinking of the centrosphere. Periodically, however, its resistance is overcome, and then crustal shortening takes place, mainly in the areas of weakness, the geosynclines.

Since the oceanic basins occupy about two-thirds of the earth's surface and their mass averages about 3 per cent heavier than that of the continents, the areas of these basins are the main subsiding ones of the earth. During the subsidence, there is, according to theory, also some deep-seated rock flowage, and especially near the junction areas between oceans and lands. This flowage differentiates out lighter masses, and these hot magmas make their way, along with great pressures, tangentially upward into the borderlands, raising them into the frame of the continents. It is these periodically compensating and inwardly moving masses of the more mobile lower part of the lithosphere that cause the thin, cold, and rigid supercrust or stratosphere (also tectonosphere) to fold and overthrust toward the neutral areas. On the other hand, the rising granitic magma may dominate in its movements, ascending like a vertical wedge into the supercrust, thrusting it aside into a bilaterally symmetric mountain chain.

North America is margined on the east by *Novascotica*, *Appalachia*, and *Antillia*. Each one of these borderlands has its own geologic structure and history. Along the west coast of North America is the greatest of all the borderlands, *Cascadia*, which later on divides into *California* and *Charlotte* masses (from Queen Charlotte Islands). *Yukonia*, occupying a great part of present Alaska, is not well enough known to say much about it, other than that in this area the seaways seemingly show that there often was a borderland here. Mexico, or *Columbia*, in Paleozoic time appears to have been a lowland and apparently with the characteristics

of a nuclear area, but in Permian time its western half became rugged or mountainous, with a geosynclinal sea over the eastern portion. It therefore appears to be a nucleus that has undergone a second cycle of crustal deformation. *Llanoria*, on the other hand, even though but a northeastern extension of Mexico during much of the Paleozoic, yet has its own history, apparently becoming actively mobile and mountainous for the first time late in the Mississippian. Finally, Arctic America is bordered by *Pearya*, part of which is now risen into the United States mountains. These borderlands are plotted on the map, figure 3, and the more important ones will now be described in more detail.

APPALACHIA

As long ago as 1856¹³ Dana defined Appalachia as "the region toward the Atlantic border, afterward raised into the Appalachians," but the actual name for the borderland was not given until 1897, and then by Williams.¹⁴ In the present connection, we will restrict the term Appalachia to the southern half of the eastern borderland lying to the north and west of Antillia; the northeastern borderland has long been known as Acadia, of which Novascotica is the outer portion (see page 162).

The western margin of Appalachia extends from about the highlands of New York southwestward into central Alabama, where this old land is overlapped along its inner side and southern end by Mesozoic and Cenozoic deposits. Across its eastern side the Atlantic Ocean began to spread for the first time in the Cretaceous, and it continued to do so periodically during the Cenozoic. How far this borderland formerly extended into the Atlantic Ocean may never be learned, even approximately, but on the basis of the very thick Devonian clastics of the Appalachian geosyncline extending from central Virginia to the Catskills, Barrell¹⁵ estimated that their volume is at least 63,000 cubic miles, or considerably more than the volume of the Sierra Nevada of California. On this estimate of sediment that was clearly derived from a highland to the east and southeast, and on the assumption that this land had the height of the present Sierra Nevada, Barrell concluded that the watershed of Appalachia in Devonian time was where the 100-fathom line of the Atlantic is now; in other words, roughly 100 miles east of New Jersey. Therefore, if the eastward slope of the watershed was like the western one, Appalachia extended out into the ocean at least 200 miles beyond the present shoreline of the At-

¹³ Dana: On American geological history. Amer. Jour. Sci. (2), vol. 22, p. 319.

¹⁴ H. S. Williams: On the southern Devonian formations. Amer. Jour. Sci. (4), vol. 3, p. 394.

¹⁵ Joseph Barrell: Upper Devonian delta of the Appalachian geosyncline. Amer. Jour. Sci. (4), vol. 37, pp. 248-249.

lantic. Since this estimate is based on clastics alone, it is probable that Appalachia extended eastward even farther than 250 miles. This land began to founder into the depths of the Atlantic (Poseidon) seemingly as early as the Jurassic period.

Was Appalachia during Paleozoic and Mesozoic times continuous with Antillia and the Bahamas? Our knowledge of dated geologic formations in Antillia does not go back of the Jurassic, and so we are left to guess what the earlier relations were. From the maps already shown, it has been seen what shape my guessing has taken. The extent of these lands is, however, circumscribed by the depths of the present oceans and the nature and distribution of the Paleozoic faunas. In any event, whatever the area and the outward form of Appalachia, it was not an independent continent; rather was it an integral part of North America. The importance of this conclusion will become apparent when we contrast geosynclines with mediterraneans (see page 194).

Later on it will be shown that to the southeast of the Saint Lawrence geosyncline lay another one, the Acadian trough (page 179). The question must now be asked, Was there also a geosyncline to the east of the Appalachian one? Our answer is that there is nothing in what remains of the western part of Appalachia to show that such a trough ever existed in this borderland. Much further than this we can not go, but from Barrell's physiographic studies of Appalachia in Devonian times it is clear that if another geosyncline was present it must have lain upward of 200 miles east of the eastern shore of the Appalachian geosyncline. Keeping in mind the present depths of the Atlantic Ocean, however, we are disposed to believe that Appalachia was throughout a highland and of the nature of a geanticline.

As Appalachia furnished nearly all of the sediments of the geosyncline that lay along its western side, we must now try to find out how often this land was reelevated. It is clearly evident that southwestern Appalachia was mountainous in earliest Cambrian time. This is seen in the immensely thick, and at first very coarse, Lower Cambrian formations of the Appalachian trough, extending from Tennessee into Alabama. Other thick clastic deposits extend northeastward in decreasing volume to New Jersey.

On the other hand, clastics in thick deposits of late Ordovician and early Silurian age increase in volume from Virginia to southeastern New York. The Silurian is also very thick and in coarse deposits in the Maritime Provinces of eastern Canada, indicating that early in the Silurian Acadia was also in highland condition.

The Lower Devonian sandstones are also widespread and extend from Georgia to New York. Their thicknesses, however, never exceed hundreds of feet, and accordingly Appalachia is not thought to have been reelevated much at this time.

In keeping with the orogeny of middle and late Devonian times throughout Acadia, we see in the very extensive and thick Devonian delta deposits of the Appalachian trough that northern Appalachia was then also a highland and not very unlike the Sierra Nevada of today.

Toward the close of the Mississippian, Appalachia was again reelevated, and the proof of it lies in the 10,000 feet of coarse deposits of the coal fields of Alabama, the widely distributed and thick Pottsville conglomerate and sandstones, and the general sandy nature of the thick deposits of Pennsylvanian time.

On the other hand, we may conclude from the very thick accumulations of Paleozoic sediments in Pennsylvania, ranging between 30,000 and 40,000 feet in thickness, that Appalachia was several times a highland during Paleozoic time. This generalized statement is further supported by the folding of the western side of northern Appalachia and presumably also of Acadia in Ordovician time, and by the very marked folding of Acadia in the late Devonian; further, the presence in the Appalachian geosyncline of thick sandstones of Lower Devonian and early Pennsylvanian ages shows that there was reelevation of the borderland at the close of Silurian and Mississippian time. Therefore, directly or indirectly, the evidence indicates that Appalachia was reelevated about six times during the Paleozoic, namely, (1) at the very beginning of the Cambrian, (2) late in the Ordovician, (3) somewhat during the Lower Devonian, (4) in the Upper Devonian, and (5) at the close of the Mississippian. Finally, (6) in the Permian came the greatest of all the crustal movements, when the borderland and the geosyncline were folded into an anticlinorium and synclinorium that together make the Appalachian Mountains, of which today we see only the roots beneath the dissected Cenozoic peneplain.

ACADIA AND NOVASCOTICA

The northeastern half of greater Appalachia, properly greater Acadia, includes the Acadian geosyncline, the New Brunswick geanticline, and the borderland Novascotica. The latter is the homologue of restricted Appalachia, and all that is left of it as dry land is a narrow strip of its inner side making up the greater part of present Nova Scotia and Cape Breton. The banks outside of these provinces and of Newfoundland are

but the submerged portion of this borderland. The width of Novascotica is unknown, but it seemingly was not less than 150 miles and may well have been of the order of 250 miles.

Novascotica appears to have been reelevated during the first half of the Paleozoic at least five times: first, decidedly toward the close of the Cambrian, as is shown in the thick and coarse clastics of earliest Ordovician time; secondly, during the last half of the Ordovician, when the Acadian trough was dry; thirdly, at the close of the Ordovician, as is attested by the thick deposits of the Silurian; fourthly, toward the close of the Silurian, when the relevation was not decided, as seen from the thin but coarse materials of the Lower Devonian; fifthly, toward the close of the Devonian, as attested by the coarse clastics of the younger Perry and Horton series. Finally, it seems probable that Acadia during Pennsylvanian time was elevated four times more, as is clearly the case for the Northumberland basin. In all, then, this or that portion of Acadia rose nine times during the Paleozoic.

CASCADIA

It appears probable that Paleozoic Cascadia extended from southern California far into the north, even beyond the Queen Charlotte Islands. On the other hand, it must also have extended many hundreds of miles to the west of the present shoreline of the Pacific Ocean, since it furnished the thick deposits of the Cordilleran geosyncline. There is, however, from time to time much uncertainty as to the exact position of the eastern shorelines of Cascadia. These uncertainties are due to the fact that but little of this vast area has been studied in detail and geologically mapped, and our knowledge is still in the main that of reconnaissance work.

Dana included in the borderland Cascadia the Sierra Nevada, Coast, and Vancouver mountains, and the ranges of western British Columbia; in fact, this entire region exhibits but rarely any sediments of Paleozoic age previous to the Pennsylvanian. This and the further fact that the sediments of the Cordilleran geosyncline thicken and become coarser to the west are the basis for postulating the long borderland Cascadia.

It is generally assumed that Cascadia was a long north-south trending continuous land, and it may have been so throughout the Proterozoic and up to the close of the Ordovician and even the Silurian. With the Devonian, but more especially in the Carboniferous, the occurrences of marine strata across parts of Cascadia are such as to indicate that even as early as these times this borderland consisted of at least two parts, the

strike of which is northwest-southeast, in harmony with the present trends of the Pacific system of mountains in California-Oregon, and again in Vancouver-British Columbia. In any event, there were, since the Tennessean, northwesterly trending channels across Cascadia, the *Shastan channel* in the south and the *Alexandrian embayment* in the north, dividing Cascadia into a smaller southern mass that may be known as the *Californian borderland*, and a much longer northern one that may be called the *Charlotte borderland* (see figures 3, 9, and 13).

There is as yet no evidence to show that Cascadia as a whole underwent marked orogeny at any time until near the close of the Jurassic, although in the late Devonian there was orogeny going on, together with volcanic action, in northern California. Diller has shown that here the Tennessean lies with an angular unconformity on the Devonian. On the basis of the sediments of the Cordilleran geosyncline, however, it is clear that Cascadia must have been a highland during the Proterozoic and again in early Cambrian time. Toward the close of the Cambrian it was a lowland and remained so until early Carboniferous time, when it was reelevated to furnish the moderately thick formations of the Tennessean and Pennsylvanian formations.

MEDIAL OR NUCLEAR AREA OF NORTH AMERICA

(See Map, Figure 3)

GENERAL DISCUSSION

Along the inner sides of the borderlands lie the several comparatively narrow geosynclines, whose waters extended at times irregularly over the medial area of the continent, the very extensive and ancient nucleus of North America. The structure of this medial area came into being long before the Cambrian, and in the main during the earlier Proterozoic, though mountains arose here as late as late Proterozoic time (Killarney Mountains).¹⁶ It was therefore the oldest part of the continent, made stiff and rigid through a vast amount of orogeny. Ever since the Proterozoic the nucleus of the continent has lain but little above sealevel, warping periodically up or down some hundreds of feet. Repeatedly, shallow seas have formed over parts of it, and yet in no place have the Paleozoic sediments accumulated to a depth of one mile. Usually these strata are measured in hundreds of feet rather than in thousands. Because the nuclear part of North America has remained so near sealevel

¹⁶ W. H. Collins: An outline of the physiographic history of northeastern Ontario. Jour. Geology, vol. 30, 1922, pp. 206-207.

it is also known as the *neutral area*. Kober has recently called these parts of the continents "Kratogens" (from *kratos*, strength, and *genos*, producing). Suess has called these neutral areas *forelands*, and it is against them that the geosynclines have been pushed and folded.

The *Canadian shield* occupies the greater northern part of the neutral region, while in the United States the Paleozoic seas more often covered its southern extension west of the Cincinnati geanticline and east of *Siouia*, which was less often warped beneath the ocean level (see figure 3). In the late Paleozoic, neutral Siouia, however, became mobile again and the site of the Ancestral Rocky Mountains geanticline (see page 186). The ancient land *Columbia*, or greater Mexico, may have been another shield, and during most of the Paleozoic it appears to have been a low-land, furnishing but little sediment to the adjacent seas.

It is most often around, and rarely across, the nuclear region that the inland or epeiric seas have flowed. Because this region has not undergone orogeny since the Proterozoic, its Paleozoic and later strata remain nearly horizontal, though in places blocks have been faulted or warped into the old masses. Accordingly, all of the flat-lying sedimentary formations around and upon the nucleus are included under the term "neutral portion of the continent"—neutral in relation to the average levels of the oceans because unaffected by mountain-making forces.

SWELLS

Undoubtedly there are many domed areas within the neutral or nuclear areas of North America, and especially within the eastern United States. In Middle Ordovician time the Cincinnati geanticline began in two swells, the Nashville and Cincinnati domes. In early Middle Silurian time these became confluent into a single arch having the general trend of the Appalachians. The Ozark dome is one of the greatest and most persistently rising of these swells, and northern Wisconsin is another but less actively rising one. The Mississippian seas have repeatedly flowed between these swells and at times have completely gone over them. On the other hand, the Sioux Falls region of southeastern South Dakota and the Baraboo range of Wisconsin are persistent Huronian quartzite ridges, remnants of the Killarney Mountains that rose in late Proterozoic time. The buried granite ridge (Nemaha Mountains) also appears to be of this orogenic entity.

GEANTICLINES

(See Map, Figure 2)

DANA'S VIEWS

Having seen that "synclinoria were made through a progressing geosynclinal," we are brought, Dana states,¹⁷ "to another important distinction in orographic geology—that of a second kind of monogenetic mountain." These are produced through evolving geanticlines, which "are simply the upward bendings in the oscillations of the earth's crust—the geanticlinal waves," or "anticlinoria." His typical example is the Cincinnati arch, though it is perfectly clear that later on he included far greater and even continental (epeirogenic) arching under the term anticlinoria. Beginning with simple, depressed, and restricted arches, the term came to be applied by Dana to all upward archings of lesser and greater extent.

"Geanticlines and geosynclines," Dana states,¹⁸ "are flexures of the strata of the earth's exterior, or the supercrust, not of the crust itself. The crust is thick, and it is impossible, were it but 10 miles thick, that it should be bent into so small and abrupt flexures. It has, however, its own great flexures of low angle and of great breadth, both upward and downward."

CINCINNATI GEANTICLINE

The Cincinnati uplift of Newberry and Safford, and the Cincinnati plateau of H. S. Williams, was defined by Dana in 1890¹⁹ as the type example of a geanticline. It has in a general way the strike of the Appalachian folds and was at times overlapped in part or wholly by the Appalachian or Mississippian seas. When the medial part was submerged, the northern end made *Cincinnati Island* and the southern one *Tennessee Island*. As two swells, the arch appeared in Middle Ordovician time, was repeatedly reelevated, and during the middle and late Paleozoic continued as a marked structural feature of the Mississippian seas. It had a width of something like 250 miles.

NEW BRUNSWICK GEANTICLINE

To the south and east of the Saint Lawrence geosyncline lay the New Brunswick geanticline, separating it from the Acadian trough. This geanticline appears to have originated at the time when the Saint Law-

¹⁷ Dana: Amer. Jour. Sci. (3), vol. 5, 1873, p. 432.

¹⁸ Dana: Manual of geology, 4th ed., 1895, p. 106.

¹⁹ Dana: Areas of continental progress in North America. This Bulletin, vol. 1, p. 41. Also Manual of geology, 4th ed., 1895, p. 387.

rence and the Acadian geosynclines on either side of it came into existence, namely, toward or at the close of the Proterozoic. This axis, beginning in the granitic area of eastern Connecticut and Rhode Island, continues across central Massachusetts into New Hampshire (the White Mountains are situated on it), thence northeasterly across central Maine into northern New Brunswick, and finally across southern Newfoundland. The width of this geanticline appears to have been on the average greater than 100 miles.

How often the New Brunswick geanticline was in upward motion is not yet known. If, however, we may judge by the nature of the coarse sediments in the Saint Lawrence trough, it appears to have been rejuvenated into a highland (1) toward the close of the Cambrian (seen in the Lauzon quartzites and conglomerates, the red Sillery, and the green Quebec slates); (2) during the later Ordovician (seen in the coarse Cincinnati and early Silurian formations); and (3) by the long-continued intermittent rising during late Silurian and middle Devonian time, which ended in the Gaspé sandstones, 7,000 feet thick.

The Ancestral Rocky Mountains geanticline and the Cordilleran Intermontane geanticline are best described in connection with the Cordilleran geosyncline (see pages 186-187).

KINDS OF GEANTICLINES

The several geanticlines or anticlinoria of North America can be grouped in three categories: Those of lesser import are (1) the low, narrow, localized arches in the interior of the continent, typified by the Cincinnati arch. The most mobile of the anticlinoria are (2) the periodically rising borderlands, such as Appalachia, which border the geosynclines oceanward. They have been described on preceding pages and need no discussion here. Then there are (3) the geanticlines that rise out of the area of a geosyncline and have seas on either side of them, as the New Brunswick, Ancestral Rocky Mountains, and Cordilleran Intermontane geanticlines.

Geanticlines may have no direct connection at all with folded mountains, as in the Cincinnati arch. In other cases a geanticline is situated on one side of an orogenic mass, as the Front Ranges of Colorado lie in front of the Rocky Mountains. In yet other cases folded mountains are present on either side of a geanticline, as the Sierra Nevadas and the Rocky Mountains on either side of the Cordilleran Intermontane geanticline. The latter appears to be the equivalent of the "Narben" and the "Zwischengebirge" of Kober's Alpine orogen.²⁰ Geanticlines and orogens

²⁰ L. Kober: *Der Bau der Erde*, 1921, p. 140.

may remain as dry lands or may sink into the depths of the oceans, as in the Dutch East Indies.

Finally, we must note the greatest upbowings of the continents that result from epeirogenic movements. These were first defined by Dana and Gilbert as the very broad and flat archings that appear long after folded mountains are made, the uplift affecting at the same time both synclinoria and anticlinoria and even parts of the far inland neutral regions. Such are the greater Appalachian uplift extending from the Atlantic Ocean to the Mississippi Valley, and the far vaster and higher Rocky Mountain arch extending from Kansas and Nebraska to the Pacific Ocean. The latter came into existence after the Miocene, and its crest is between 5,000 and 7,000 feet above sealevel, on the top of which are situated the protuberant remainders of the previously made synclinoria and anticlinoria.

PROTEROZOIC GEOSYNCLINES

(See Map, Figure 1)

When it became apparent that the Cordilleran and Appalachian geosynclines were in existence in earliest Cambrian time, it was thought desirable to learn when they originated. The writer therefore took Van Hise's correlation papers for the Archean and Algonkian²¹ and plotted on a map of North America the late Proterozoic deposits (Keweenawan and Animikie). Copies of this map were then sent for criticism to the following geologists in this country and Canada: Arthur Keith, Eleanor Bliss Knopf, Anna I. Jonas, Edward Sampson, D. F. Hewett, F. J. Alcock, C. K. Leith, and J. J. O'Neill. The map (figure 1) here presented is the result of this assistance, for which the writer is very thankful. The shorelines as plotted must, of course, be conjectural, and all that is really valuable is the general trends and positions of the four seaways: (1) Appalachian, (2) Cordilleran, (3) Ontarian, and (4) the greater Arctic sea. The southern opening of the Appalachian geosyncline and the southern and northern ones of the Cordilleran troughs are also highly conjectural. It may be that Daly's northern continuation of the latter waterway into the Arctic Ocean²² is more correct than that shown in figure 1 of this address.

The *Cordilleran geosyncline* is the longest enduring trough and came into existence early in the Proterozoic. During this era there was de-

²¹ C. R. Van Hise: Correlation papers—Archean and Algonkian. U. S. Geol. Survey, Bull. 86, 1892.

²² R. A. Daly: Geology of the North American Cordillera at the forty-ninth parallel. Geol. Survey Canada, Mem. 38, 1913, p. 202.

posited here a maximum depth of more than 37,000 feet of strata, though the individual sections range in thickness from 10,000 to 27,000 feet. There are almost no volcanic materials. The formations are distinctly bedded clastics, with practically no conglomerates, composed chiefly of fine-grained sandstones and shales with a moderate amount of impure limestone and dolomites that contain considerable iron carbonate and silica.²³ They are all shallow-water deposits, the argillites are often banded, rippling and mud-cracking are common, and sometimes also salt crystals. Purple and red colors are not common, the prevailing shades being greenish, bluish, grayish, or whitish tints. Basal conglomerates occur only to the west, and Schofield²⁴ says that the sandstones become coarser in the same direction; therefore a land lay to the west. This is the borderland Cascadia, which came into existence probably earlier than the Cordilleran geosyncline. Toward the top of the Beltian series in southern British Columbia occur 300 to 5,000 feet of lavas and sills.

Toward the top of the Beltian series, in association with the limestones and dolomites, algal deposits (*Cryptozoon*-like forms) are common and at times make up thick beds. Walcott²⁵ has also described annelid tubes, and to the writer these fossils suggest marine waters rather than fresh or even brackish ones.

In northeastern Utah the Uinta reddish (ferruginous) quartzites with some greenish shales are, according to Powell,²⁶ 12,500 feet thick. They rest unconformably upon Archeozoic formations.

In the Grand Canyon of Arizona occur, according to Walcott,²⁷ 12,000 feet of more or less red strata, beginning at the top with the Chuar sandy shales (5,120 feet). Below are the Unkar sandstones and sandy shales (6,830), with some calcareous shale and limestone below (435), along with lava flows in the upper part. All of the Grand Canyon series is near-shore deposits and much of it is even of fresh-water origin. The sediments came from the north and west.

In the southern *Appalachian geosyncline* Keith informs the writer that the late Proterozoic formations consist of lava flows, tuffs, and slates, the flows predominating at the northwest, where land is therefore indicated.

²³ F. C. Calkins: A geological reconnaissance in northern Idaho and northwestern Montana. U. S. Geol. Survey, Bull. 384, 1909.

²⁴ S. J. Schofield: Geology of the Cranbrook map-area. Geol. Survey Canada, Mem. 76, 1915.

²⁵ C. D. Walcott: Pre-Cambrian Algonkian algal flora. Smithson. Misc. Coll., vol. 64, 1914, pp. 77-156; Pre-Cambrian fossiliferous formations. This Bulletin, vol. 10, 1899, pp. 199-244.

²⁶ J. W. Powell: Report on the geology of the eastern portion of the Uinta Mountains. U. S. Geol. and Geog. Survey Terr., vol. 7, 1876.

²⁷ C. D. Walcott: Pre-Carboniferous strata in the Grand Canyon of the Colorado, Arizona. Amer. Jour. Sci. (3), vol. 26, 1883, pp. 437-442.

In the Pennsylvania-Maryland area they make up the Glenarm series, and in New York the equivalent formations are the Lowerre, Inwood, and Manhattan (Jonas). The thickness is something like 10,000 feet.

In Nova Scotia the Gold-bearing series consists of a lower quartzite group about 11,000 feet thick and an upper graphitic and ferruginous slate group about 4,000 feet in depth.

In southeastern Newfoundland the Proterozoic series is over 11,000 feet thick, and consists of coarse quartzites, slate conglomerates, slate, and diorites.

The Ontarian geosyncline (so named because best developed in Ontario Province) embraces the Animikian, or Iron series, of but little disturbed, dark, carbonaceous (6-10 per cent) slates and sandstones, with iron-bearing chert and jasper and impure limestones and dolomites. In the Penokee area of Michigan the portions remaining have a thickness of 14,000 feet, but elsewhere they are much thinner. These strata are held to be of marine origin.

The Animikian series is followed by the Keweenawan sediments, usually of a red color, and metal-bearing volcanics (seemingly plateau flows, largely diabase and basalt). In the Lake Superior region the lower conglomerates and sandstones, with impure limestones and shales, have a thickness of from 300 to 1,400 feet. They may be of marine origin. Then comes the middle series, probably wholly of continental origin and upward of 30,000 feet thick, of which at least five-eighths is igneous material, the rest being red conglomerates and sandstones. The upper series attains locally to 20,000 feet, most of which is sandstone of fresh-water origin, derived from the volcanics.

The Ontarian geosyncline is the oldest known trough of North America. It probably had its origin during Archeozoic time, since all of the older Proterozoic deposits, and even the Grenville series of Ontario, likewise have the alignment of the younger series.

The greater Arctic sea is not regarded as a true geosyncline. The sediments are largely sandstones, with some slate. It is interesting to note this late Proterozoic marine invasion, since it recalls the four similar floods of Ordovician and Silurian times.

DEVELOPMENT OF THE APPALACHIAN GEOSYNCLINE

(See Maps, Figures 4 to 12)

GEOSYNCLINES IN GENERAL

In North America the geosynclines all lie on the inner or continental side of borderlands (see map, figure 3). Their deposits are thickest

toward the borderlands and thin out over the neutral area or the nucleus of the continent. In the east is the smaller *Appalachian geosyncline*, and in the western part of the continent the greater *Cordilleran geosyncline*. The latter finally evolves into the *Rocky Mountain* and *Pacific sequent geosynclines* of Mesozoic times. To the east of the Appalachian geosyncline in greater Acadia is the small *Acadian geosyncline*. Finally, there is in the Arctic region, on the inner side of the borderland Pearya, the *Franklinian geosyncline*.

EMBAYMENTS

Besides these geosynclines, but in connection with them, there is in the southern part of the continent the *Ouachita embayment*, uniting with the Appalachian geosyncline, while the southern end of the Cordilleran geosyncline has the *Sonoran embayment*, extending transversely across Nevada, New Mexico, Texas, and Sonora (see map, figure 3).

GREATER APPALACHIAN GEOSYNCLINE

The Appalachian geosyncline, in the widest sense, extends from the southeastern corner of Labrador and northern Newfoundland along the western side of Acadia and Appalachia into the Gulf of Mexico. At the northeast it appears to have been continuous with what is now the North Atlantic, but during the Paleozoic, with Poseidon, an ocean to the north of the transverse equatorial land Gondwana. At the southwest the trough appears to have continued unbroken into the Gulf of Mexico and across Tehuantepec into the Pacific Ocean.

As previously stated, the Appalachian trough was in existence early in Proterozoic time. Beginning with the Lower Cambrian, it appears earliest in Alabama, Georgia, and Tennessee, and long before the close of this epoch the trough was continuous from the Gulf of Mexico northeast to Newfoundland. The deposits of Cambrian time are much the thickest in the southern part of the trough and are from Appalachia, then a mountainous land. On the other hand, in the northeastern part of the geosyncline the sediments are much thinner. It should be said that in the main the clastics throughout the greater Appalachian trough came from the east and southeast. In all of this we see that the isostatic relations of the sinking geosyncline to the rising eastern lands were reestablished during the crustal movements taking place toward or at the close of Proterozoic time.

Thus far we have spoken of the greater Appalachian geosyncline as a continuous trough, and so it is from the structural viewpoint; but from the local sedimentary histories it is plain that there are here combined

two confluent geosynclines, with at times very dissimilar developments stratigraphically, faunally, and even orogenetically. For these reasons the term Appalachian geosyncline, in the restricted sense, will refer to the trough south of Vermont, while to the one northeastward of Massachusetts we will apply the term *Saint Lawrence sea*, made familiar to us by the Canadian geologists and James D. Dana. It should be remembered, however, that there appears to be no sharp geographic boundary between them. Furthermore, both troughs during Lower and Middle Cambrian times appear to have spread either confluent or singly across New Jersey and the southern New England States into the Atlantic Ocean (Poseidon). From Upper Cambrian time into the Devonian the two geosynclines were structurally more or less confluent, though their seas were at times not continuous. On the other hand, the Saint Lawrence geosyncline often brought into the interior seas of America parts of north European faunas, while the Appalachian one continued into the Antillean mediterranean, having south European and South American faunal connections.

RESTRICTED APPALACHIAN GEOSYNCLINE

The sedimentary history of the actual Appalachian geosyncline continued from the beginning of Cambrian to the close of Pennsylvanian time, and it was a far more persistent, longer enduring, and more deeply subsiding trough than the Saint Lawrence geosyncline. Then, too, this periodically subsiding trough was more often filled with variably extensive shallow seas, and these at times were continuous with the waters of the Saint Lawrence geosyncline. Previous to the Middle Silurian, the Appalachian seas often spread widely also into the Mississippian sea, but after the completion of the Cincinnati arch the floods were restricted to the eastward of this geanticline.

The Appalachian trough was more or less completely drained of its marine waters at least eight times (Middle Cambrian, close of Beekmantown, close of Ordovician, Guelph, close of Silurian, late Devonian, and twice during the Mississippian). It is certain, however, that locally it was dry far more often than eight times, but this matter can be made plain only through a detailed statement of the history of the trough, and this is not the occasion to present the succession of paleogeographies.

Sedimentation in the Appalachian geosyncline was by no means continuous nor uniform in the rate of deposition. The Cambrian and Ordovician are in best development south of Pennsylvania, while the Devonian is almost restricted to north of Tennessee. The Cambrian and Ordo-

vician records are most complete in the south and less so in the north. Then in Middle Silurian time a transverse swell developed throughout eastern Tennessee, and the subsequent seas were far more persistent north of this State than in the southern part of the geosyncline. This swell was especially active in pushing the shorelines to the westward in the area south of Virginia during late Silurian and most of Devonian time. On the other hand, during Middle and Upper Devonian and Mississippian times, the seas again spread eastward to the region of the earlier Appalachian shores. The shoreline was farthest east during the Lower Cambrian and early Ordovician, but it can not be said that it moved progressively to the west with each recurring sea. We have just pointed out the irregularity in position of the eastern shore for the trough south of Virginia. It would, furthermore, appear as if the shore moved irregularly westward for a time, followed, in some cases at least, by a quick return to a more easterly position with the incoming of new seas. In any event, we see more easterly shores during Lower Cambrian, Canadian, Mohawkian, Lower and Middle Silurian, Middle Devonian, and Mississippian times. During Pennsylvanian time the shore moved progressively to the west, with the final blotting out of the Appalachian trough in the orogenic movements beginning in this period and culminating in the early Permian.

From the previous statements we again see what is now so well known, namely, that the transgressions of the oceans upon the continents are periodic in appearance, and more or less irregular in their spreadings. The successive paleogeographies show, however, that the pattern of the seaways is fairly alike—a condition that is governed by the variable movements of the geanticlines and the swells.

Nor do the floods always first appear in the Appalachian geosyncline and then spread inland variably over parts of the neutral area. This is true in some cases, but in others the transgressions pass up the Mississippi Valley or down from the Arctic and then extend more or less toward or into the geosynclines. The greatest of Paleozoic floods did not originate in the geosynclines, but came from the Arctic across the western part of the Canadian shield into the United States. This is seen in the floods of the middle and late Ordovician, the earlier Silurian, and again in the Devonian. Rarely did any of these floods fully occupy the eastern geosynclines. In this extraordinary variability of the marine transgressions we see that at times the Appalachian geosyncline is above the strand-line while the neutral areas are in flood, and at other times the trough is filled with seas when the interior of North America is land.

In other words, the sealevel attitude of the neutral area is not always in keeping with the periodic sinkings of the geosyncline below sealevel. Accordingly, there appears to be an irregular alternation between land and sea conditions in the Appalachian, the Mississippian, and the neutral areas.

Since the Appalachian trough is the type area on which geosynclinal structures are based, let us look a little more deeply into the local rock quantities and times of sedimentation, so that we may learn more as to the nature of its irregularly subsiding bottom. Accordingly, we will present something of this detailed sedimentation along seven different lines across the geosyncline.

(1) *Northwest-southeast through Kingston, New York.*—In this area the maximum of sinking appears not to exceed 15,000 feet. The generalized section is about as follows:

	Feet
Cambrian	1,500
Ordovician	4,000
Silurian (Shawangunk, 300; High Falls, 500; Cement series, 35)	835
Devonian (Helderbergian, 250; Oriskany, 180; Esopus-Onondaga, 375; Hamilton, 1,300; Portage, 3,000; Chemung, 1,725; eroded away, 500) ..	7,330
Mississippian eroded away	500
	14,165

(2) *Northwest-southeast through northern New Jersey.*—Here the maximum of sinking appears to be about 23,000 feet. The generalized section is as follows:

	Feet
Cambro-Ordovician (Chickies, 1,000; Kittatinny, 3,000)	4,000
Ordovician (Jacksonburg, 150; Martinsburg, 3,000)	3,150
Silurian (Shawangunk, 1,600; High Falls, 2,300)	3,900
Devonian (Lower, 400; rest, 8,500)	8,900
Mississippian (Susquehanna area)	2,000
Pennsylvanian (Anthracite area)	1,500
	23,450

(3) *Through Maryland and southern Pennsylvania.*—This area appears to be the second greatest subsidence (see 7), and the old Proterozoic land in the deepest part of the trough has gone down about 35,000 feet. The detail is as follows:

	Feet
Lower Cambrian (Antietam, 800; Harpers, 2,750; Weverton, 1,250; Tomstown, 1,000; Waynesboro, 1,250; Elbrook, 3,000)	10,050
Cambro-Ordovician (Conococheague, 1,635; Beekmantown, 2,300)	3,935
Ordovician (Stones River, 1,050; Chambersburg, 750; Martinsburg, 2,000; Juniata, 400)	4,200

	Feet
Silurian (Tuscarora, 270; Clinton, 920; Cayugan, 1,450).....	2,640
Devonian (Helderbergian, 300; Oriskany, 400; Romney, 1,400; Jennings, 4,800; Hampshire, 4,700).....	11,600
Mississippian (Pocono, 1,800; Mauch Chunk, 2,000).....	3,800
Pennsylvanian, 3,100; Permian only in west, 1,200.....	4,300
	40,525

(4) *Through central Virginia and West Virginia.*—It appears that in this area the trough did not subside more than 25,000 feet. The formations are as follows:

	Feet
Cambrian, probably.....	8,000
Ordovician (Shenandoah, 2,400; Martinsburg, 2,000; Massanutten-Juniata, 1,000).....	5,400
Silurian (Tuscarora, 600; Rockwood, 700; Cayugan, 700).....	2,000
Devonian (Helderbergian, 200; Oriskany, 300; Middle, 1,300; Upper, 5,000)	6,800
Mississippian (Pocono, 500; Greenbrier, 1,000; Canaan, 1,200).....	2,700
Pennsylvanian, probably.....	4,000
	28,900

(5) *Through northeastern Tennessee and southwestern Virginia.*—The subsidence here appears not to have exceeded 20,000 feet. The thicknesses are about as follows:

	Feet
Cambrian, 9,000; Ordovician, 6,000; Silurian, 1,000; Devonian, 300; Mississippian, 3,600; Pennsylvanian, 5,000.....	24,900

(6) *Northwest and southeast through Knoxville, Tennessee.*—The subsidence here is at least 30,000 feet. The thicknesses are about as follows:

	Feet
Cambrian, 18,000; Ordovician, 8,000; Silurian, 1,200; Devonian, 50; Mississippian, 2,100; Pennsylvanian, 2,000.....	31,350

(7) *Northwest and southeast through northern Alabama.*—Here the subsidence is greatest, being around 38,000 feet. The detail is as follows:

	Feet
Cambrian (Weisner, 10,000; Beaver, 1,000; Rome, 800; Conasauga, 3,000)	14,800
Ordovician (Knox, 4,500; rest, 3,500).....	8,000
Silurian, 1,200; Devonian, 1,000; Mississippian, 3,250.....	5,450
Pennsylvanian (Warrior field, 3,500; Cahaba, 5,500; Coosa, 10,000)	10,000
	38,250

An analysis of the seven sections just given shows that the bottom of the Appalachian geosyncline has subsided in the line of its strike into at

least two major rock basins.²⁸ In eastern central New York (Albany) the depression is probably somewhere near 8,000 feet. From here southward the trough becomes ever deeper, and in western Maryland it appears to have gone down about 35,000 feet. Thence the bottom rises again to the Virginia-Tennessee State line to about 20,000 feet, only to sink rapidly in the Knoxville area to about 30,000 feet and to about 38,000 feet in northeastern Alabama. What has gone on to the southward is not ascertainable because of the Mesozoic overlaps from the Gulf of Mexico.

Just as the trough bottom evolved in long undulations along its strike, so in transverse directions it became more or less waved. This is best seen in the narrow but long continuance of the very thick Lower Cambrian deposits in the southern part of the Appalachian geosyncline. Here these strata in the eastern part of the trough attain a thickness of about 15,000 feet, and thin rapidly to the west. The trough in early Ordovician time was a far wider subsiding syncline, and in the middle part of this period the extreme eastern portion appears for a time to have been divided into several long and narrow seaways.²⁹ In the Maryland region the Appalachian sea during Lower Cambrian time was also a narrow one, and here accumulated about 10,000 feet of strata. Then came wider seas transversely, and they accumulated in their deepest part another 10,000 feet during Ordovician and Silurian time. Over all came the great Devonian-Mississippian delta, so ably pictured by Willis and Barrell,³⁰ depositing another two miles' depth of strata. Finally, in the comparatively narrow Cahaba coal field of Alabama was deposited, according to Butts,³¹ 10,000 feet of early Pennsylvanian sediments.

In all of this we see that the Appalachian geosyncline during its growth evolved along its strike into at least two great basins of deposits, while transversely the trough was variably wrinkled, changing more and more from a simple syncline into a complex geosyncline. These greater undulations of the bottom of the trough and of the older Paleozoic formations should not be confounded with the later superimposed foldings due to

²⁸ Ulrich in his "Revision of the Paleozoic systems," this Bulletin, vol. 22, 1911, p. 562, divides the Appalachian geosyncline into five basins, as follows: (1) northeastern Pennsylvania, (2) Maryland, (3) central Virginia, (4) Tennessee, and (5) Alabama.

²⁹ See Ulrich: *Op. cit.*, p. 412.

³⁰ Bailey Willis: *Paleozoic Appalachia, or the history of Maryland during Paleozoic time*. Maryland Geol. Survey, vol. 4, 1902, pp. 23-93.

Joseph Barrell: *Op. cit.*

³¹ Charles Butts: *The southern part of the Cahaba coal field, Alabama*. U. S. Geol. Survey, Bull. 431, 1911, pp. 89-146.

Charles Butts and E. O. Ulrich: *Mississippian formations of western Kentucky*. Kentucky Geol. Survey, 1917, p. 118.

lateral compression, when the geosyncline and the borderland were folded into the Appalachian polygenetic mountains.

SAINT LAWRENCE GEOSYNCLINE

(See Maps, Figures 3 to 8)

The northeastern half of the greater Appalachian geosyncline, extending from eastern New York and Massachusetts to east of Newfoundland, is known as the Saint Lawrence sea. The strata along the northwestern shore of the Saint Lawrence River, and to the west of Lake Champlain as well, still remain undisturbed. They are the materials farthest removed from the source of main supply, the highlands of the New Brunswick geanticline to the southeast and east. These deposits are chiefly limestones of Cambrian, Ordovician, and Silurian ages and the thicknesses are usually small. Along the eastern side of the Adirondacks there is less than 5,000 feet; about Quebec there appears to be less than 1,500 feet; farther northeast, across the Mingan and Anticosti islands, there is about 4,000 feet, and in southeastern Labrador less than 500 feet remains. How far these shallow seas spread over the Canadian shield is unknown, since this most positive part of North America has usually been above the strandline and is now stripped of nearly all the marine deposits which once rested on it. Ordovician strata are known, however, about Lake Saint John and elsewhere in Quebec, and since those that remain are of the kinds deposited far from shores, it appears safe to postulate that most of the seas of the Saint Lawrence geosyncline spread several hundred miles to the northwest of the Saint Lawrence River.

To the southeast of the great river and estuary, however, all the strata of the Saint Lawrence geosyncline are in greatest confusion, being folded, crumpled, and widely thrust in superimposed sheets, and intruded by igneous masses nearest the geanticline. This superimposed structure is due in smallest part to the orogeny of late Devonian time, when the trough was, however, completely blotted out; the greatest deformation came with the time of most marked compression and thrusting, during the Pennsylvanian and Permian. All geologists have found it exceedingly difficult to unravel the stratigraphic sequence here, and as well to determine the thicknesses of the formations. The greatest thickness of strata appears to be in the Gaspé area, where there may have been as much as 20,000 feet. In northwestern Newfoundland there appears to have been 15,000 feet of subsidence, while to the southeast of Quebec and Montreal the formations may attain a similar thickness. In northern Vermont the total deposition may not exceed 8,000 feet, and in Massachusetts

and eastern New York there seems to be a considerably smaller thickness. In all of this we see that the Saint Lawrence trough was a subsiding area from early Cambrian time to the close of the Devonian, and that nowhere did more than 20,000 feet of subsidence take place. This greater sinking toward the northeastern and oceanic end of the trough was accentuated by the Gaspé delta of Devonian time, where 2,000 feet of limestones and 7,000 feet of sandstones were deposited.

The seas of the Saint Lawrence trough at many different times continued confluent into the Appalachian geosyncline. Its sedimentary history is also far less complete than that of the Appalachian trough, and accordingly the whole or the medial length of the Saint Lawrence geosyncline was oftener dry land; at least five times was it completely drained of all seas. It was dry during the Middle Cambrian and again at the close of the Cambrian, between Beekmantown and Chazy times, and again in earliest and latest Silurian times.

It has been stated that the Saint Lawrence trough was blotted out by the late Devonian orogeny. The question must be asked, Were there here earlier times of folding? For three-quarters of a century geologists have been pointing out the Taconic disturbance that took place toward the close of the Ordovician. The area of this folding is known definitely to extend from Tristates, New York, northeastward past Kingston to Becraft Mountain, east of the Hudson River, where all overlapping and definitely ascertained Devonian strata cease. The intensity of folding increases from west to east and from southwest to northeast. The distance of known folding in a straight line is about 125 miles, and it appears reasonable to assume that this orogeny extends many hundreds of miles northeast of Hudson, New York, and to the west of the New Brunswick geanticline. As yet the unconformity can not be determined in the intensely folded slates of the Ordovician and Cambrian farther to the northeast. On the other hand, there is not the slightest evidence that Silurian or Devonian formations were ever present on the western side of the Green Mountains, but to the east of these mountains there is paleontologic evidence of late Silurian, and, in Massachusetts, of Middle Devonian time. These facts appear to indicate that the eastern side of the whole of the Saint Lawrence trough was folded toward the close of the Ordovician. Furthermore, the succeeding Silurian deposits along the southeastern side of the Saint Lawrence trough are thick deposits of sandy shales and impure limestone, indicating that the New Brunswick geanticline had been reelevated. In these occurrences we see that the eastern portion of the Saint Lawrence trough was folded throughout east-

ern New York and perhaps all the way to Newfoundland, where there are also known crustal movements of late Ordovician time. Furthermore, as we shall see later on, the whole of the Acadian trough on the other side of the New Brunswick geanticline was dry land during the middle and late Ordovician. Other local details might be mentioned, all of which point to a time of folding and elevation of the eastern portion of the Saint Lawrence geosyncline extending clearly from New Jersey to Vermont and possibly all the way to Gaspé, Quebec.

Before leaving the Saint Lawrence geosyncline, it should be stated that the Canadian shield was the northwestern lowland of this trough. Its other shore was the periodically rising New Brunswick geanticline, a narrow highland tract described earlier (page 166). To the southeast of this geanticline lies another geosyncline, the Acadian trough, next to be described.

DEVELOPMENT OF THE ACADIAN GEOSYNCLINE

(See Maps, Figures 3 to 8)

GENERAL DISCUSSION

Across the southeastern margin of the New England States and through the central parts of the Maritime Provinces of Canada and southeastern Newfoundland, a geosyncline developed during Cambrian, Ordovician, Silurian, and Devonian times. Dana in 1890³² called it the *Acadian trough*, and its southwestern end, of longest endurance, the *Fundy basin*. During its earlier history it extended from at least southeastern Newfoundland southwestward across Cape Breton, northwestern Nova Scotia, southern New Brunswick, southern Maine, and eastern Massachusetts. Like the Appalachian geosyncline, it appears to have been in continuance as a trough since early Proterozoic time (see map, figure 1). To the southeast of the Acadian trough lay the borderland Novascotica, of unknown width, while its northwestern shore was made by the New Brunswick geanticline, which separated it completely from the greater Saint Lawrence geosyncline.

The Acadian trough was present in Lower Cambrian time, and is seen in better development during the Middle Cambrian, with its *Paradoxides* faunas of European affinities, extending from southeastern Newfoundland to Boston. Then there is no evidence of this trough until early Ordovician time (Bretonian), when again it has decided European faunas. During all the rest of the Ordovician the trough appears to have

³² Dana: Archæan axes of eastern North America. Amer. Jour. Sci. (3), vol. 39, p. 380. Also Manual of Geology, 4th ed., 1895, pp. 444, 461, 536.

been dry land, making its reappearance early in the Silurian (Clinton) as an open marine channel depositing coarse clastics, and continuing to the end of Guelph time. These Silurian faunas are very much like those of Wales and are best known about Arisaig, Nova Scotia. During the Upper Silurian the sedimentary record is restricted to its westward end, the Fundy basin, laying down here considerable thicknesses of marine strata, but more especially great volumes of volcanic ash and lavas. These center about the southeastern corner of Maine. The Fundy basin continued with marine waters throughout Lower Devonian time, and later in this period the whole of the trough was involved in the marked foldings of the Acadian disturbance.

The total subsidence of the Acadian trough apparently did not exceed 12,000 feet (County Antigonish, New Brunswick), though in the very limited and highly volcanic area of southeastern Maine the total sinking may have been as great as 25,000 feet. Elsewhere the deposits appear to average around 6,000 to 7,000 feet. The total thicknesses are as follows:

	Feet
Southeastern Newfoundland (Cambrian, 2,120; Ordovician, 3,880)	6,000
County Antigonish, New Brunswick (Cambrian, estimated, 1,000; Ordovician, 5,800; Silurian, 3,600; Lower Devonian, 680)	11,080
Saint John, New Brunswick, and southeast (Cambrian, 2,150; Ordovician, 700; Silurian and Devonian, estimated, 3,500)	6,350
Eastport, Maine (Cambro-Ordovician, 4,000; Silurian marine, 6,000; Silurian volcanic, 14,000; Devonian, 1,000)	25,000
Eastern Massachusetts	10,000

NORTHUMBERLAND BASIN

(See Maps, Figures 10 to 12)

With the late Devonian orogeny, as previously stated, the Acadian geosyncline was blotted out, and then new areas of fresh water with some marine sedimentary accumulation came into being. This embayment, consisting of a series of troughs, may be known as the Northumberland basin because it is best developed throughout the lands bordering the strait of this name in New Brunswick and Nova Scotia. It continued across the Saint Lawrence Gulf and Newfoundland, and the deposits are of Mississippian and Pennsylvanian time. They average in New Brunswick and Nova Scotia between 15,000 and 18,000 feet. It is interesting to note that these basins of deposits lie between periodically rising mountains, and that these mountains were reelevated four times more before the whole of the Northumberland basin was, in Permian times, brought above the level of sedimentary accumulation.

As we have seen, the Northumberland basin came into being with the late Devonian orogeny, which was followed by fresh-water deposition of early Mississippian time (Horton, 2,000 feet) and by late Mississippian marine deposits (Cheverie, 700 feet, and Windsor, 1,200 feet). Then the Northumberland basin underwent mountain-making for the second time, and, so far as known, this movement completely shut out marine transgressions until the origin of the present Gulf of Saint Lawrence. Following this second elevation, more than 5,000 feet of coarse continental deposits of early Pennsylvanian time were laid down in valleys between mountains. Then came the third reelevation of the mountains, followed by 6,800 feet of coarse sediments, also having many coal strata whose floras indicate Middle Pennsylvanian time. Finally came the fourth uplift, giving rise to from 2,100 to 6,000 feet of more or less red beds of latest Pennsylvanian time, and then the whole of the Northumberland basin was reelevated in the early Permian for the fifth time.

In all of this we see that the Acadian region was intensely folded and intruded by igneous rocks during the late Devonian orogeny, and that it then underwent four widely spread times of seemingly vertical uplift, with a final elevation in the Permian. Even so, these are not all of the times this region underwent one or the other kind of crustal movement, since the early Paleozoic formations of the Acadian geosyncline show in the nature of their coarse sediments that the borderland Novascotica had been uplifted in late and early Silurian times, probably also in the Ordovician, and at the close of the Middle Cambrian.

DEVELOPMENT OF THE OUACHITA EMBAYMENT

(See Maps, Figures 5 to 11)

One of the interesting phenomena in the stratigraphy of North America is the appearance in Upper Cambrian time of what seems to be the beginning of a geosyncline all along the north side of the Mexican old land known as *Columbia* and its northeastern extension, *Llanoria*. It was a seaway that united the Cordilleran trough with the Appalachian one, but it lasted only into Middle Ordovician time.

Beginning in eastern Arkansas, the Cambro-Ordovician deposits of this trough are seen emerging from underneath the Mississippi embayment of Mesozoic and Cenozoic formations. They have a maximum thickness of about 1,500 feet, increasing westward to 7,000 feet in the Arbuckle Mountains of eastern Oklahoma (Wichita Mountains have 5,000 feet). Thence southwardly these deposits decrease rapidly in thickness to central Texas, where, in Llano and Burnett counties, the

depth is about 1,800 feet. In southwestern Texas, about El Paso, the maximum thickness is about 1,700 feet, and a smaller depth continues across southern New Mexico into Arizona. To the south, in Sonora, Dumble has reported about 3,000 feet of limestones beneath supposedly Upper Ordovician formations that may be of Cambro-Ordovician time. On the other hand, while the two ends of this trough (Ouachita and Sonoran embayments), and particularly the former, continued to accumulate strata intermittently throughout the Paleozoic, yet the longer central reach across Arizona, New Mexico, and Texas was dry land during Silurian, Devonian, and Mississippian times. In all of this we see that there was a good beginning for the development of a long transverse syncline, and that it failed to evolve into a geosyncline because the land elements Columbia and Siouia, or the Great Plains country, remained neutral or slightly positive in relation to the oceanic level. In other words, we see that Columbia was not in motion northward; only its northeastern portion, Llanoria. The latter was a decidedly positive and periodically rising crustal element that eventually moved northward, crowding the strata of the Ouachita embayment against the ancient granitic Ozark dome. Because the Ouachita trough had not the usual length of geosynclines, and since it was often dry land, it is preferably regarded as a southwestern embayment of the Appalachian geosyncline. Undoubtedly the causation for the Ouachita embayment was the decided negative condition of the southernmost portion of the Appalachian geosyncline that was evolving toward a deep Gulf of Mexico. The compensating reaction of this sinking area against Llanoria, on the other hand, caused it to be a decidedly positive element, and especially so after Mississippian time. As we shall see, Llanoria was the highland that furnished the tens of thousands of feet of clastic sediments for the Ouachita trough of Pennsylvanian time.

The Ouachita embayment, as previously stated, emerges from beneath post-Paleozoic deposits at Little Rock, Arkansas, and the petroleum wells about the Wichita Mountains of Oklahoma show that the trough did not extend beyond these mountains. Therefore this embayment had a length of about 400 miles. To the east of Little Rock it must have continued unbroken and in open connection with the Appalachian geosyncline. As is well known, Branner³³ long ago pointed out that the Appalachian trough appeared to continue into the Ouachita embayment. It is now certain, however, that the line of strike of the formations of Arkansas can not be connected with the last of those in Alabama, where the Appa-

³³ J. C. Branner: The former extension of the Appalachians across Mississippi, Louisiana, and Texas. *Amer. Jour. Sci.* (4), vol. 4, 1897, pp. 357-371.

lachian folds plunge beneath the Cretaceous overlap. The exact stratal connections between these two troughs may never be known because of the very wide Mesozoic-Cenozoic covering of the Mississippi Valley. On the other hand, the Paleozoic faunal connections of the Ouachita embayment with those of the Mississippian seas are more intimate than they are with those of Alabama. In other words, the seaway connections on the basis of the faunas are more intimate with the Mississippian sea than with the southern end of the Appalachian trough.

The Ouachita embayment appeared early in Upper Cambrian time and its waters remained more or less continuously as a recording seaway into the early Middle Ordovician. The deposits are mainly dolomites, and vary in thickness from 1,500 feet in eastern Arkansas to 7,000 feet in the Arbuckle Mountains of eastern Oklahoma, and to 5,000 feet in the Wichita Mountains, farther west.

During Middle Ordovician time the southern end of the neutral area Siouia was warped above sealevel, blotting out the medial reach of the long transverse seaway formerly uniting the Ouachita embayment with the Sonoran embayment, and hence from Mohawkian time onward the former trough is restricted to Oklahoma and Arkansas. From Middle Ordovician time up to the close of the Mississippian, the Ouachita embayment was only intermittently filled with marine waters, and therefore during this long interval the deposits are not in great volume. They vary from about 1,200 feet in central Arkansas to about 2,400 feet in the Arbuckles. Then a most marked change took place in the land to the south of the Ouachita embayment, and Llanoria must have been elevated most decidedly, since the Pennsylvanian strata in Arkansas attain, according to Branner, to a depth of over 23,000 feet. The total maximum thickness of all Pennsylvanian formations in southeastern Oklahoma appears to be about 37,000 feet, though the general average in any place may not exceed 28,000 feet. In other words, the whole of the eastern two-thirds of the Ouachita embayment sank during the Paleozoic nowhere less than 25,000 feet, and to the east of the Arbuckle Mountains, the region of greatest depression, it appears to have gone down about 35,000 feet. Shortly after Pottsville time all of the trough in southern Arkansas began to fold into the Massern Mountains. In Oklahoma, however, the folding took place later, and according to McCoy³⁴ it came at the close of Monongahela or just before Cisco time. The thrusting is toward the north and northwest.

³⁴ A. W. McCoy: A short sketch of the paleogeography and historical geology of the Mid-Continent oil district and its importance to petroleum geology. Bull. Amer. Assoc. Petrol. Geologists, vol. 5, 1921, pp. 541-584.

The whole relation of subsequent sedimentation was changed by the orogeny of late Pennsylvanian times and by another movement in eastern Colorado and New Mexico. This latter area of mountain-making is described by Lee in one of the papers of this symposium, under the name of "Ancestral Southern Rocky Mountains." To the east of the latter lay the Permian shallow-water seas of Texas, Oklahoma, and Kansas, laying down great sheets of clastics derived from the west, along with the most extensive deposits in North America of sodium chloride and gypsum. On the other hand, the Arbuckle and Massern mountains remained as land athwart the late Pennsylvanian and Permian seas, but the Wichitas were finally completely submerged by Permian sediments. In Nebraska, Kansas, and Texas, however, the Pennsylvanian seas continued unbroken into Permian time.

From the previous statements we see that the Ouachita embayment and its positive borderland, Llanoria, are as striking a geologic element in the evolution of the North American continent as are the Appalachian geosyncline and its borderland, Appalachia. The only marked difference is the lesser areal extent and the less complete marine record of the southern elements. On the other hand, the positive crustal movements in both areas appear to be harmonious and of the same orogenic realm.

DEVELOPMENT OF THE CORDILLERAN GEOSYNCLINE

(See Maps, Figures 4 to 17)

GENERAL DEVELOPMENT

The longest and widest, and by far the oldest and longest-continuing seaway is the one long known as the Cordilleran geosyncline. During the Paleozoic it extended from the Arctic Ocean southward through what is now the mountainous region of western North America into northwestern Mexico, a distance of 3,000 miles. In Canada the width of this seaway is usually several hundred miles, while in the United States it is many hundreds of miles wide and at times attains a breadth of more than 1,000 miles. The eastern shores of this vast geosyncline and its marine extensions are the Canadian shield and its southern prolongation, Siouia, while its oceanward borderland is Cascadia, to the west of which is the Pacific Ocean.

With the close of the Devonian the Cordilleran seas begin to restrict and their eastern shores in the far north begin to move westward. This change is further accentuated in the late Pennsylvanian and Triassic, so that by the end of Jurassic time there had arisen, almost out of the very center and along the entire length of this geosyncline, the very extensive

Cordilleran Intermontane geanticline. In Cretaceous times, then, there lay on the western side of this geanticline the *Pacific geosyncline*, with a length of at least 2,500 miles, and on its eastern one the *Rocky Mountain geosyncline*, or Coloradoan sea, extending in the form of a sigmoid curve from Behring Straits into the Caribbean mediterranean, a distance of over 5,000 miles.

EARLY CORDILLERAN GEOSYNCLINE

(See Maps, Figures 4 to 12)

Just when the Cordilleran geosyncline came into existence is not known, but it is certain that its central part was present early in Proterozoic time, and seemingly with about the same position and extent as in the early Paleozoic (see map, figure 1). Its presence is clearly evidenced by the vast deposits of Proterozoic time in the Beltian series, extending certainly from Great Salt Lake into British Columbia to about 55 degrees north latitude. Furthermore, in the Grand Canyon area of Arizona other thick Proterozoic deposits are known, so that we may say that the Cordilleran geosyncline in Proterozoic time had a regional distribution similar to that which it had during the early Paleozoic. These Proterozoic deposits, mainly sandstones and shales and with very little of limestones or igneous materials, vary in thickness from 15,000 to over 30,000 feet, and as their depth and coarseness increase westward, it is also clear that even then Cascadia was, as later on, the bounding western borderland. Probably the most extraordinary fact in our present studies is that of the conformable relations of the Proterozoic and Paleozoic strata. In other words, there was no marked orogeny in the Cordilleran geosyncline at the close of the Proterozoic as there clearly was in all the other marginal areas of North America. Can this tranquillity of the American Cordilleran region mean that the North Pacific Ocean was not a decidedly sinking region during the Proterozoic, and that this vast basin did not begin to become crustally unstable until late Jurassic time, when the evidence of vast mountain-making appears for the first time in many lands that bound the Pacific Ocean? As yet we know of only local orogeny in the Cordilleran region of North America during Proterozoic and Paleozoic time. Therefore one of the extraordinary phenomena in the geologic history of the Cordilleran region is the conformability of Proterozoic, Paleozoic, and even Mesozoic formations up to the close of the Jurassic.

The thicknesses of the Paleozoic formations throughout the western part of the Cordilleran geosyncline vary between 10,000 and 23,000 feet, being apparently greatest in the southern half. The Cambrian,

Ozarkian, and early Ordovician deposits are very thick throughout the geosyncline, varying between 6,000 and 16,000 feet. It is the grandest known Cambrian sequence anywhere in the world, and our knowledge of it is almost wholly due to Walcott. The Middle and Upper Ordovician and all of the Silurian may be absent or are poorly represented, apparently by not over 500 feet in thickness, in the medial length of the geosyncline, while the later Devonian is usually present, though never thicker than 1,000 feet. About middle Mississippian time a great change took place in the extreme northern portion of the trough, since the whole Mackenzie region was then warped above sealevel, and this area did not again have deposits until Jurassic time. Therefore it is only in the southern two-thirds of the Cordilleran geosyncline that the later Mississippian, Pennsylvanian, early Permian, and Triassic are present in thick deposits, varying in depth between 1,500 and 5,500 feet. In other words, we agree with Ulrich that the Paleozoic sequence in the Cordilleran seas is far less complete than that of the Appalachian geosyncline, and that the latter area is best "fitted to fill the requirements of a standard" for stratal correlations in America. These conclusions therefore appear all the more strange when we take into consideration the fact that the Cordilleran seas, when present, were often more extensive than were those of the Appalachian trough.

RISE OF THE ANCESTRAL ROCKY MOUNTAINS GEANTICLINE

(See Maps, Figures 2 and 12)

We must now make a little digression to explain the rising of a geanticline in the eastern portion of the Cordilleran geosyncline, one that is clearly described by Lee (see page 286) as the Ancestral Southern Rocky Mountains. All through the earlier Paleozoic the Cordilleran seas transgressed eastward on and at times across the neutral region Siouia. In the same way the Mississippian seas spread westward variably over parts of Siouia. These conditions continued until late in the Tennesseean. Then, apparently early in Pennsylvanian time, at least all of eastern Colorado and New Mexico, western Kansas, western Oklahoma, and northwestern Texas was bowed up into the high Ancestral Rocky Mountains geanticline. To the west of this highland lay the Cordilleran seas of late Paleozoic time, while to the east of it the Mississippian seas of late Pennsylvanian time and the following Red Beds Permian overlapped to the westward. In other words, the source of sediments for these seas was completely changed by this geanticline. Finally, we learn from Lee that the whole of this arch was eroded to sealevel by late Jurassic time, since the Logan sea, and more especially that of the Cretaceous, completely transgressed it.

LATE CORDILLERAN GEOSYNCLINE

(See Maps, Figures 12 to 17)

We now return to a further consideration of the Cordilleran geosyncline, and more especially to its changes after Devonian time. It has been shown that this trough had a uniform development throughout the Proterozoic and early Paleozoic. For the first time crustal deformation set in late in the Devonian, but only locally in northern California (Shastan channel); and a little later, in the Mississippian, upwarping took place over a very wide region in the Mackenzie River area, completely blotting out here the Cordilleran geosyncline. With these movements we see Cascadia transgressed more definitely by the Shastan channel and the Alexandrian embayment, and taking on northwest-southeast trends that bring about the further delimitation of its parts into the borderlands, California and Charlotte. In consequence the inland seas of Carboniferous times also took on northwest-southeast trends. This new alignment of lands and seas is seen even better in late Pennsylvanian time, but here the areal expanse of the seas is still very extensive and much like the conditions earlier in the Cordilleran geosyncline.

RISE OF THE CORDILLERAN INTERMONTANE GEANTICLINE

With the continued rising of the Ancestral Rocky Mountains, the Cordilleran sea of Middle and Upper Triassic time was pushed westward, blotting out gradually the whole of the medial portion of this old geosyncline. Finally, early in the Jurassic there began farther west the rising of the Cordilleran Intermontane geanticline, which during the Cretaceous separated two independently evolving geosynclines. This greater arch, however, was not completed until after the close of the Jurassic, for the Logan sea of early Upper Jurassic time was still in wide marine connection with both the North Pacific and the Arctic oceans. Finally, toward the close of the Jurassic, followed the Sierra Nevada orogeny—a time of marked mountain-making throughout the length of western North America, but chiefly in the area of the Cordilleran Intermontane geanticline. This further rising of the geanticline extended it unbroken as a marine barrier from Siberia into Central America and brought into existence two new and wholly distinct sequent geosynclines—sequent because of their formation out of the greater and older Cordilleran geosyncline—the Rocky Mountain one on the east and the Pacific trough to the west of this geanticline. This arched land exists today as the Northern Interior, Columbia, and Nevada-Sonoran high plateaus of Ransome.³⁵

³⁵ F. L. Ransome: The Tertiary orogeny of the North American Cordillera and its problems. In "Problems of American geology," 1915, pp. 287-376.

PACIFIC SEQUENT GEOSYNCLINE

(See Maps, Figures 12 to 17)

Let us first consider the shorter and narrower Pacific geosyncline, but one with a far longer history than the eastern or Rocky Mountain trough. It extended from the Alexandrian archipelago of southeastern Alaska to the southern end of Lower California, and while its main history is of Mesozoic time, yet during the whole of the Cenozoic the Californian sea was a decidedly subsiding geosyncline. Actually there were, however, two more or less distinct Pacific geosynclines with different histories. To the northern one, restricted almost wholly to Canada and essentially of Mesozoic time, it is proposed to give the name of *British Columbia geosyncline*, while the southern one, of much longer endurance, has long been known as the *California sea*.

All through the Paleozoic the *Alexandrian embayment* of southeastern Alaska was in evidence, and its seas, beginning with the Silurian and continuing with interruptions up to the close of the Permian, laid down apparently not less than 12,000 feet of sediments, though the depth may be a great deal more (see maps, figures 7 to 17). With the late Pennsylvanian, however, this embayment became but the northern part of the British Columbia geosyncline, and the eastern shoreline of the northern part of the Cordilleran trough was moved far to the west. This northern geosyncline of late Paleozoic time continued unbroken into the Californian sea, which at this time still retained its former wide eastern spread. The British Columbia geosyncline, however, was not in typical development until Upper Triassic time, and was blotted out during the earlier Upper Cretaceous, long before the Rocky Mountain trough was folded into mountains.

The Triassic deposits of the British Columbia geosyncline attain a maximum depth, on Vancouver Island, of 13,000 feet, but nine-tenths of this is volcanic extrusives. The Jurassic is well represented by from 3,000 to 8,000 feet of deposits. Of earliest Cretaceous strata there are none, and the sea returned in late Lower Cretaceous times and continued unbroken into that of the Pierre, during which interval there were deposited from about 4,000 to 15,000 feet of coarse clastics and lava flows. In other words, the whole of the trough subsided, from the Middle Pennsylvanian to the close of the Cretaceous, something like 25,000 feet.

Now let us consider the southern half of the Pacific sequent geosyncline, or, better, the Californian sea. The Shastan channel was clearly in evidence with the Middle Devonian, and the Cordilleran seas did not become narrowed until Middle Triassic time. Therefore it was in the Upper Triassic that the Californian geosyncline made its appearance.

It extended from Oregon south to the end of Lower California. During Mesozoic time it subsided not less than 27,000 feet, and to this must be added the Paleozoic strata, amounting to something like 8,000 feet more. Toward the close of the Cretaceous large parts of the trough were folded, roughly in what is now the Great Valley of California and the Coast Ranges; then during the Cenozoic the trough continued to receive marine and fresh-water sediments that on the average will probably exceed 30,000 feet in depth. The stratal history of Lower California is too little known to go profitably into its detail except to say that it is best known since early Upper Cretaceous time.

The orogeny of the late Cretaceous does not appear to have been of a very marked character, since in places the Mesozoic and Cenozoic deposits are conformable to one another. Orogeny was more pronounced at the close of the Oligocene, strongly so at the end of the Middle Miocene (Monterey), moderately at the close of the Miocene, and most pronounced of all at the close of the Pliocene.

In the evidence recited we see that northeastern California subsided during the Paleozoic and up to the close of the Jurassic something like 22,000 feet, and following the rise of the Cordilleran Intermontane geanticline central California sank during late Mesozoic and all of Cenozoic time probably as much as 45,000 feet.

ROCKY MOUNTAIN SEQUENT GEOSYNCLINE

(See Maps, Figures 14 to 17)

We have seen that early in Lower Cretaceous time there came into full existence the Cordilleran Intermontane geanticline. To the east of this long arch, that continued to rise throughout Cretaceous time, there gradually developed the Rocky Mountain geosyncline that in full development extended from Siberia into the Caribbean mediterranean. This vast subsiding realm is readily divisible by its structural features into three areas. In the north (1) is the Arctic-Mackenzie region, (2) south of the Liard River into northern New Mexico is the very wide Rocky Mountain or Dakotan sea, and (3) from southern New Mexico and Arizona south is the Mexican area.

Let us take up first the *Mexican geosyncline*, since the marine transgression begins earliest here. Nearly all of Mexico was land throughout most of the Paleozoic, and the only parts frequently under water were the narrow southern Tehuantepec region and the greater Sonoran embayment across Sonora, Arizona, Chihuahua, New Mexico, and western Texas. As yet, it can not be said with certainty that Mexico has the characteristics of an ancient shield, and that it was a low land throughout

Paleozoic time, though we may for the present assume this condition because of the relatively thin deposits of the Sonoran embayment.

The Mexican geosyncline made its appearance in the north late in Pennsylvanian time, then in the south late in the Triassic, more definitely early in the Jurassic, and before the close of this period its waters had attained Texas. Then there was a retreat of the sea from the north, but early in the Lower Cretaceous a general transgression of the Mexican sea set in, that widened until it finally covered more than two-thirds of Mexico. It continued to spread northward into the United States, and early in the Upper Cretaceous (Benton) the Mexican waters united with the Dakotan sea, that since late Lower Cretaceous time (Blairmore) had been spreading southward. The maximum thickness of the Mesozoic deposits in Mexico may be as great as 20,000 feet.

The Arctic coast of Alaska is too little known to determine whether there is here a geosyncline having a borderland facing the Arctic Ocean. The older Paleozoic formations have been found to be some thousands of feet thick, followed in the Cape Lisburne area by more than 5,000 feet of Lower Carboniferous. The Jurassic, wholly of continental strata, is 15,000 feet thick, followed by about 5,000 feet of Cretaceous. This region, for easier reference, may be known as *Endicott sea*.

The stratal history of the Mackenzie Valley in its broader aspect has been made known during the past ten years, and it is now established that, beginning with the Lower Cambrian, there was no orogeny in this region until late Cretaceous time. Not even the late Jurassic rising of the Cordilleran Intermontane geanticline affected the area of the Mackenzie Valley or, for that matter, any of the region of the Rocky Mountain geosyncline. Here during Cambrian to late Devonian times the Cordilleran trough received no less than 13,000 feet of marine strata. Then the region was warped above sealevel, and there are no strata of any kind until late Jurassic time, when the overlaps of the British Columbia geosyncline toward the east attained the region of the Mackenzie Valley. The making of the Cordilleran Intermontane geanticline followed, but in this region the arch apparently was not a highland, since to the east of it the Cretaceous deposits do not exceed a few thousand feet in thickness.

It was during the late Lower Cretaceous (Blairmore-Albian) that the Arctic Ocean began to spread south through the Rocky Mountain geosyncline, but these marine waters seemingly did not extend south of the Peace River of Alberta, though fresh-water coal-bearing strata of about this time (Kootenai) occur southward through Alberta into Montana. Then the seas retreated northward, or, better, their spreading appears

to have been oscillatory during Lower Cretaceous time, just as were the Comanchian (Washita) seas spreading from Mexico northward to make the Dakotan sea. Finally, in early Upper Cretaceous (Benton) time, the Rocky Mountain geosyncline was at its height of flood, making the largest inland sea that ever lay upon the North American continent. It then extended continuously from the Arctic Ocean into the Caribbean mediterranean, and from British Columbia, Idaho, and Utah eastward into Manitoba, Minnesota, Iowa, Kansas, and eastern Texas. Along the western side of the trough from Wyoming north into Alberta, from 10,000 to 20,000 and locally even 25,000 feet of coarse clastics were laid down. Toward the east all the formations thin away rapidly to a few thousand feet in depth. However, soon after the fullness of this great sea the northern end of the geosyncline began, in Niobrara time, according to Dowling,³⁶ to warp above sealevel. The higher arching continued to spread southward during the remainder of Cretaceous time, causing the wide Coloradoan sea to change into a continually southwardly shrinking gulf, and the last of its marine waters (Cannonball) were blotted out just before Fort Union time.³⁷ Fresh-water formations, however, continued to accumulate for a time (Fort Union, Puerco, Torrejon), and finally, late in the Paleocene or, more exactly, just before Wasatch time, came the second and most marked time of late Cretaceous orogenies, transforming the Rocky Mountain geosyncline into the mighty Cordillera of western North America. The folding and thrusting was away from the geanticline and toward the east. On the other hand, as the eastern mountains of the Pacific system appear to be folded and thrust away from the Intermontane geanticline, we see in parts of the polygenetic Cordilleras of western North America another example of bilaterally symmetrical mountains.

We must return once more to the sediments of the Rocky Mountain geosyncline to bring out the striking fact that in the area of greatest subsidence—that is, in Idaho, western Montana, southeastern British Columbia, and southwestern Alberta—there had been no orogeny from early Proterozoic time until the close of the Cretaceous. During this vast time there was laid down in this area about 20,000 feet of Mesozoic strata, resting conformably upon 26,000 feet of Paleozoic formations, and these in turn lie conformably upon about 30,000 feet of but little metamorphosed Proterozoic rocks. It is the longest accessible geological section known anywhere and attests the striking fact that *the earth's crust may subside at least 14 miles before it becomes folded into mountains.*

³⁶ D. B. Dowling: Summ. Rept., Geol. Survey Canada, 1921, 1922, pp. 79B-90B.

³⁷ T. W. Stanton: The Cannonball marine member of the Lance formation. U. S. Geol. Survey, Prof. Paper 128, 1920.

SONORAN EMBAYMENT

(See Maps, Figures 1, 5 to 11)

The Sonoran embayment was an east-west trending seaway in connection with the Cordilleran geosyncline during Paleozoic time. It appears to have come into being during the Proterozoic. There is, however, no region of North America less known geologically than northwestern Mexico, and therefore the history of this embayment can be given only in the light of the strata known in southern Arizona and New Mexico and southwestern Texas. There may, therefore, be in this area many more horizons than are now recognized. We have already given the Cambro-Ordovician history and pointed out that the thickness of these deposits may attain a maximum of 3,000 feet (page 182). The uppermost Ordovician and the Middle Silurian appear to be well represented by about 1,500 feet of sediments, mainly limestones. The Upper Devonian and the Lower Mississippian are also well represented by about 1,500 feet of clastics and limestones, while the thin Upper Mississippian is known only in southwestern Texas. In middle Pennsylvanian time the western end of the Sonoran embayment was blotted out by mountain-making, and then the eastern part of the Cordilleran sea opened out southeastward across Chihuahua and Coahuila into the Gulf of Mexico.

Then the thickest stratal development in this trough appeared, in middle and late Pennsylvanian and earlier Permian times; these deposits in southwestern Texas may exceed 10,000 feet of clastics and limestones. It is by all means the best marine section of these times anywhere in North America. With the middle Permian, this earliest appearance of the Mexican geosyncline vanishes and the region remains dry land until the Lower Cretaceous, when the Comanchian seas of the Gulf of Mexico spread westward across Chihuahua into eastern Sonora and northward across eastern New Mexico into Kansas. Of these Lower Cretaceous strata the thickness may not exceed 3,000 feet. All in all, it appears that no part of the Sonoran embayment sank in Paleozoic times over 20,000 feet, and it is more probable that the maximum thickness of deposits in any one place is not over 15,000 feet.

DEVELOPMENT OF THE FRANKLINIAN GEOSYNCLINE

(See Maps, Figures 3, 5 to 13)

We will now study the stratal history of the extreme northern end of North America. Explorers have been bringing scattering geologic knowledge out of Arctic North America for nearly a century, but, due espe-

cially to the concentrated work of the Norwegians (Per Schei) and the Danes (Lauge Koch) during the past twenty-five years, we are now seeing far more clearly the general stratigraphic sequence and the broader structural relations of this region. Our knowledge is best for Ellesmereland and northernmost Greenland, where it appears that there is a maximum of deposition exceeding 21,000 feet. The Arctic seas began to spread over the Archean formations in Upper Cambrian times, and thence until the close of the Triassic the sequence is about as complete in the Franklinian geosyncline as in any of the other American troughs. Upper Cambrian, Ozarkian, and basal Ordovician times are well represented by from 5,000 to 8,000 feet of more or less clastic strata, the rest of the Ordovician and Silurian by about 4,000 feet of limestones, the Devonian by 6,000 feet or more of mainly clastics, while the Carboniferous limestones and Triassic shales may considerably exceed 3,000 feet. The strata thicken and become coarser toward the north and northwest in the very areas of the most intense folding of the United States Mountains, first made known by Lieutenant Peary. These mountains have peaks up to 8,000 feet and are the northernmost range of the earth, extending from Cape Morris Jesup to Robeson Channel and across it into Grant, Grinnell, and Peary lands. The thinning out of the strata is toward the southeast across Greenland and southward through the Franklin Archipelago and the Northwest Territory of Canada, parts of the vast Canadian shield.

It is interesting to note further that northern Ellesmereland (Grant Land) and Peary Land are margined by Archean rocks, and they are to be interpreted as remnants of the borderland that furnished most of the detritals for the Franklinian geosyncline. This old land may be known as *Pearya*, and how far it extended into the present Arctic Ocean is, of course, unknown. Since the depths of this ocean north of Greenland and the Franklin Archipelago are not nearly as great as farther northward, it may have had a breadth of many hundreds of miles. That we are dealing here with a borderland having along its inner side a geosyncline whose waters lapped upon the Canadian shield is attested by the position and trend of the United States Mountains and by the further fact that the folding and overthrusting, according to a personal conversation with W. Elmer Ekblaw, is away from the Arctic Ocean and toward the southeast.

Koch³⁸ refers the making of the United States Mountains to the Cale-

³⁸ Lauge Koch: Stratigraphy of northwest Greenland. Meddel. dansk. geol. Foren., vol. 5, no. 17, 1920, pp. 1-78. Preliminary report upon the geology of Peary Land, Arctic Greenland. Amer. Jour. Sci. (5), vol. 5, 1923, pp. 189-199.

donian deformation of late Silurian time, but, since at least the Pennsylvanian strata are involved in the folding, it is clear that the origin of these ranges can not be older than late Pennsylvanian time. On the other hand, the Triassic strata appear to be unfolded and may represent a transgression restricted to the southwestern and more open remainder of the Franklinian geosyncline.

NATURE OF MEDITERRANEANS COMPARED WITH GEOSYNCLINES

GENERAL DISCUSSION

The American theory of geosynclines is widely accepted by the Europeans, but their typical area for this structure is the mountains of south-

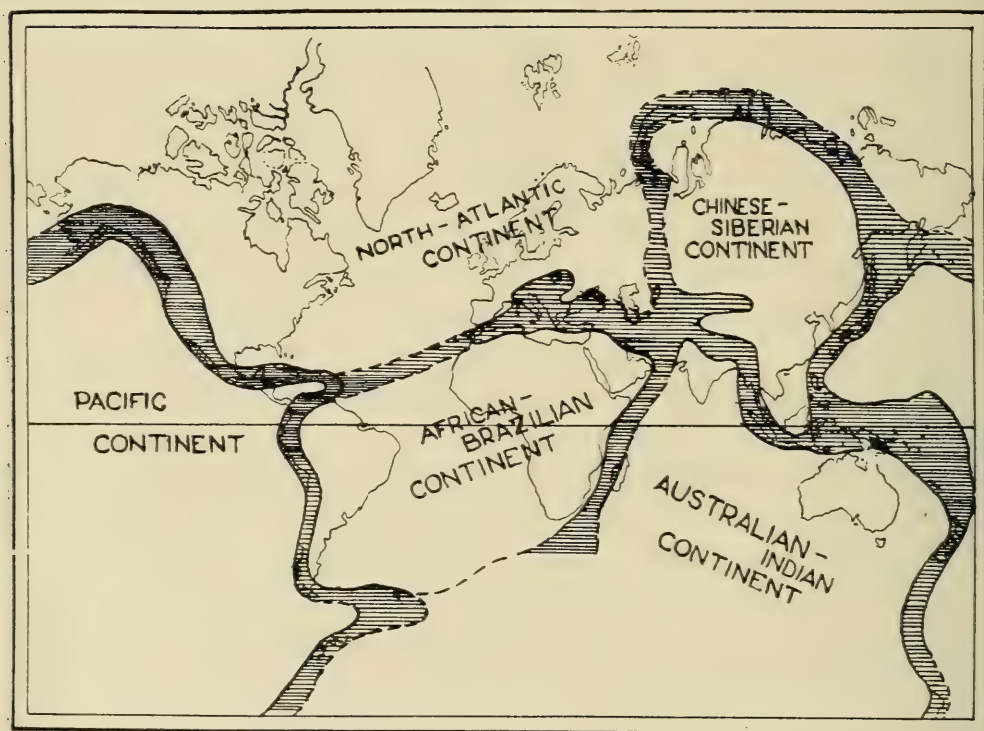


FIGURE 18.—World Chart showing Geosynclines and hypothetic Continents during Mesozoic Time

After Haug, 1909, from Ruedemann, 1922.

ern Europe and the Roman Mediterranean, extending into Asia, the site of a former greater mediterranean (see figure 18). To this very extensive seaway of the geologic past, Suess many years ago gave the name Tethys. Since Tethys was the consort of Oceanus, we see in this linkage of the gods also the idea that mediterraneans have the characteristics of oceans. This is true of mediterraneans in nearly all of their physical aspects except as to size and shape, since their typical form is that of elongate

oceans that are much more completely hemmed in by continents. It is true, however, that both types of marine areas are greatly depressed deep-water basins *situated between continents*. Geosynclines, in the American sense, on the other hand, are long and narrow shallow-water *inland seas* lying wholly upon a continent (see map, figure 3).

As the grandeur of European geology lies mainly in the mountains of the Mediterranean countries, their history and orogenies are well known, and it was but natural for the geologists of Europe to apply the term geosyncline to the area of the Tethyan deposits; all the more so since Dana, the author of the term, used it in several senses. He says:³⁹

"That there were profound geosynclines over the oceanic basins during the later Tertiary and early Quaternary is put beyond question by the fact of the great continental elevations of the same time. The Coral Island subsidence, announced by Darwin in 1839, recognized such geosynclines; and they were long since set forth by Dana as the counterpart of the continental movements."

It is, therefore, but a natural conclusion for Pirsson to say⁴⁰ that geosynclines as well as geanticlines "may occur on the continents, as well as on the ocean floor."

From these quotations we see that the term geosyncline has been altered from the original sense of Hall to the wider one of Dana, and that it is now applied to all marine basins of long-continued sinking and stratal accumulation. This condition of things has become so thoroughly engrafted in the literature of geology that it is probably impossible to change it. We will therefore use the term geosyncline in the generic sense, as extended by Dana, and apply it to all the greater long-continued down-flexured parts of the lithosphere. With this limitation, rifts and graben are excluded.

Of such crustal flexures, there are at least four categories. These are as follows:

MONOGEOSYNCLINES

The true geosynclines as originally defined by Hall and Dana, which finally give rise to but one synclinorium, are exemplified by the Appalachian geosyncline. They are long and comparatively narrow, deeply subsiding, but always shallow-water, smaller, primary geosynclines, situated within a continent along the inner side of borderlands. They should hereafter be known as *monogeosynclines*, because they are the simplest of geosynclines.

³⁹ J. D. Dana: *Manual of geology*, 4th ed., 1895, pp. 936-937.

⁴⁰ L. V. Pirsson: *Text-book of Geology*, Pt. I, *Physical geology*, 2d ed., 1920, p. 305.

POLYGEOSYNCLINES

These are the more or less wide and longer-enduring but shallow-water primary geosynclines, which give rise to one or more parallel geanticlines and to two or more sequent geosynclines with shorter histories. In other words, they are primary and greater geosynclines within a continent and situated along the inner sides of borderlands, but evolving into two or more sequent geosynclines separated by geanticlines. The typical example is the Cordilleran primary trough, out of which have arisen the Cordilleran Intermontane and Ancestral Rocky Mountains geanticlines and the subsiding Pacific and Rocky Mountain sequent geosynclines. They may be known as the *polygeosynclines*, the prefix suggesting that several geosynclines are combined.

Another fine example is the *Andean polygeosyncline*. This great geosyncline, in its size and complex history, reminds one much of the Cordilleran trough, and it was in the making throughout the Paleozoic and Mesozoic. To the west of it lay a wide borderland, first determined by Burckhardt⁴¹ for Jurassic time and fractured into the depths of the Pacific during the Cenozoic. This downfracturing was especially active during the Pleistocene and it was in keeping with the very marked up-faulting of the Andes, raising the late Cenozoic peneplain at least 10,000 feet into the Alta Plana of present Bolivia. To the east of the Andean polygeosyncline is the Brazilian shield, the nucleus or neutral area of South America, and over its western part occasionally spread in earlier Paleozoic time the waters of the western seas. As in North America, the thickest deposits are in the west nearest the borderland.

It appears that the width and degree of geologic complexity in the structure of the geosynclines are dependent on the magnitude of the nearest ocean. In other words, the greater the ocean, the wider the trough.

In eastern North America the comparatively narrow Appalachian monogeosyncline ceased to subside in the Pennsylvanian, and during the Permian the folded structure of the Appalachian polygenetic mountains was completed. Never again was this region subject to orogeny, and the width of the folded tract is about 450 miles. The region has, however, been arched several times since.

The orogenic region of western North America is, on the other hand, not less than 1,100 miles wide—that is, from eastern Colorado to California—and in this area have originated, inside of the borderlands, three geosynclines and two geanticlines. We are therefore led to believe that

⁴¹ C. Burckhardt: Beiträge zur Kenntniss der Jura- und Kreideformation der Cordillere. Paläontographica, vol. 50, 1900, pp. 1-144.

this very wide and long-enduring polygeosyncline is so because of its developmental relation with the vastness of the Pacific, the greatest of oceans.

MESOGEOSYNCLINES, OR MEDITERRANEANS

The mediterraneans are the areally smaller and decidedly elongate, but most mobile oceans, and are more completely bounded by continents than are the true oceans. They are characterized by abyssal waters, by excessive mobility, and by very intricate histories, combining eventually several geanticlines and geosynclines. The Roman Mediterranean is the best known example, and, to distinguish this type from the other geosynclines, they may be known as *mesogeosynclines* (with reference to their position between continents) or simply as mediterraneans.

In Europe the theory of geosynclines centers in the structure of Tethys and is set forth in the great work of Haug.⁴² He defines them as follows:

"The geosynclines, essentially mobile regions of the earth's crust, are always situated between two continental masses or relatively stable regions. They constitute, before their filling with sediments, marine depressions of quite a considerable depth" (page 632). "It is evident that the folded mountain chains have in general become emergent geanticlines, and divide the primitive geosyncline into secondary ones. After the folding phase the whole is again depressed, the geanticlines are again covered by the sea, and the same phenomena are reproduced in the same order up to the emergent condition" (page 708).

Again:

"Most often the strata of the geosynclines belong to the bathyal type. . . . American writers have always taken as a point of departure for their theories on mountain-making the fundamental idea that mountains are formed on [inside of] the border of oceans, and that the continents increase by the addition of other chains, more and more recent. [The last part of this sentence is not an American idea.] Under this hypothesis, geosynclines take birth at the limit between continents and oceans, the sediments which accumulate there are exclusively littoral, and the zone of sinking, with the greatest thickness of strata, is separated from the ocean by a simple swelling."⁴³

From these quotations we see that Haug's theory of geosynclines is far from the American conception of the evolution of the continent of North America as described in this address. In the first place, the continent was much larger in Proterozoic time than it is now, and parenthetically it may be added that the writer holds most of the continents

⁴² E. Haug: Les géosynclinaux et les aires continentales. Contribution à l'étude des transgressions et des regressions marines. Bull. Soc. Géol. de France, 3d ser., vol. 28, 1900, pp. 617-711.

⁴³ E. Haug: Traité de géologie, 1907, pp. 160, 166.

to have been originally larger than they are now. Nor are the geosynclines "at the limit between continents and oceans"—that is, they are not on the continental shelves. The monogeosynclines and polygeosynclines are situated hundreds of miles within the continents, inside of borderlands that are not mere "simple swellings."

We therefore see that mesogeosynclines are not situated upon a continent, but that they, like the oceans, lie between the continents. Also that their depth is oceanic in kind and their deposits range from clastics to the finest abyssal oozes. The entombed faunas are almost always normal marine ones, and even though they are often of shallow-water kinds, yet great thicknesses of almost unfossiliferous limestones and dolomites occur, suggesting for them abyssal waters. The mesogeosynclines have very long histories, and their structures show a far more complicated succession of orogenies and geanticlinal formations than do even the polygeosynclines; they are ever so much greater in area, depth of water, and in complicated structure than the monogeosynclines. On the other hand, it does not appear from what is known of the mesogeosynclines that they were ever completely drained of their waters, as was commonly the case with the monogeosynclines and polygeosynclines. In other words, the geosynclines within the continents reveal many more breaks in sedimentation than do the mesogeosynclines that lie between the continents.

The depth of water in Tethys appears to have been very unlike in different places. The Roman Mediterranean still has a length of about 2,200 miles and a greater width of over 1,000 miles. Its average depth is about 4,500 feet, while the western deep goes to 12,200 and the eastern one to 14,700 feet. Asiatic Tethys from Turkey to Burma is now mountain land, and its Paleozoic deposits indicate deeper waters than those of the Mesozoic, while the Cenozoic formations are essentially shallow-water clastics; none of the deposits, however, suggest abyssal depths, as do some of the formations of western Tethys. In late Paleozoic and Mesozoic times the eastern Tethyan mesogeosyncline extended across southern Burma and Siam, through the Dutch East Indies, to New Guinea. This eastern extension of greater Tethys, along with its folded and decidedly overthrust mountains, has been subsiding into the oceanic abyss since early Cretaceous time; here, too, the sediments with their oceanic faunas often also suggest very deep waters.

These facts and inferences indicate that the mesogeosynclines are oceanic in character, duration, and geologic work accomplished, that they clearly are not comparable to monogeosynclines, and only in a general way are like polygeosynclines.

Haug, seeing clearly that mesogeosynclines lie between continents, and that the marine loading areas of today are situated upon the outer edges of the continents—the continental shelves—postulates these same places for the geosynclines of Mesozoic time. However, continental shelves have not the trough structure of geosynclines, and to get such troughs here during Mesozoic time, Haug postulates and maps continents, though with a great deal of doubt, over the entire areas of the present oceans! Accordingly, his theory calls for mesogeosynclines; but his making land of nearly all the oceans leads us to ask, What has become of all the marine water of Mesozoic time? Of course, he can give no answer. We can partially help him out of his difficulty by postulating (1) for the greatest geosynclines an *inter*-continental position—that is, the mesogeosynclines and oceans—and (2) an *intra*-continental position for the polygeosynclines and monogeosynclines. At present the earth is without active geosynclines in the sense of those of Mesozoic and Paleozoic times. The continental shelves are not geosynclines, since they have no outer borderlands.

At the present time there appear to be no monogeosynclines in formation, unless it be (1) the Baltic Sea and Gulf of Bothnia making their way into the White Sea, or (2) the Persian Gulf heading through Mesopotamia into the Mediterranean. The Red Sea is a rift sea, with depths down to 6,000 feet, and the Gulf of California, with a major depth of over 10,000 feet, appears to be another.

Of polygeosynclines there also appear to be none now in formation. In regard to mesogeosynclines, the Mediterranean is clearly one and the Caribbean another.

The island arcs off eastern Asia inclose the Sea of Okhotsk (depth to 12,000 feet), Japan Sea (10,500), Eastern Sea, and China Sea (16,100). The Yellow Sea appears to be nearly filled with sediments, since the greater part has depths less than 400 feet, but a small outer part goes down to over 7,700 feet. These recording basins can not be grouped into any of the mentioned types of geosynclines, since some of them have oceanic depths, but all are actually a part of the Asiatic continent. They are marginal geosynclines or *parageosynclines* (geosynclines beside a continent) and contrast with mesogeosynclines that lie between continents.

OCEANS

The largest sinking fields are, of course, the oceans, with their downfractured or downwarped parts of continents, their geanticlines, and their mountains of extrusion that are either single, clustered, or arranged in

lines. Oceans, however, are not geosynclines. Suess in 1909 wrote Ruedemann:

"I do not believe in oceanic geosynclines. No existing ocean has a synclinal structure, except by superimposed sediments, and the Pacific troughs [deeps] are not synclinals."

CONTINENTAL FOUNDERING

RIFTS AND GRABEN

Rifts, even when filled with marine waters, are not geosynclines. They are, Gregory says,⁴⁴ "formed by the subsidence of strips of the earth's crust between parallel faults." The Great Rift Valley is the grandest example. This series of fault-formed valleys is continuous from Palestine to south of the Zambesi of southern Africa, and branches of it extend from the Gulf of Aden westward to the central Congo. The Red Sea is one of its marine invaded parts, with depths down to 6,000 feet, but the rift has "a total downthrow of 11,000 feet."

The Great Basin country of the United States is another example, with a much wider area of downthrow, which is something like 4,000 feet in Utah.

The rifting of eastern Africa is generally believed to be due to settling of an uplifted arch of epeirogenic extent. Krenkel⁴⁵ has shown, however, that the rifts cut all the geologic structures, none of which give unmistakable evidence of an extensive arch. He states that Africa is being squeezed between the southwardly moving mass of Asia and the northwardly pushing mass of the Antarctic Ocean. In consequence, Africa is moving northwestward. On the other hand, the Indian Ocean resulted in the foundering of eastern Gondwanaland, or, better, Lemuria, that began in Cretaceous time. Because of all these interacting movements, the outer crustal portion of eastern Africa has been widened about 5 per cent, the compensation for this enlargement giving rise to rifting on a grand scale. This increase in area and faulting through tension has gone on in compensation for the orogeny elsewhere. Therefore *tafrogenesis* (from the Greek for rifts or graben) is the counterpart of orogenesis, and East Africa is the type area for tafrogenic structures. Rifts also develop in mesogeosynclines, and one of the best examples is the Ethiopian mediterranean of Neumayr. It began to develop as a marine trough, about Permian time, between Africa and Lemuria, and persisted as such

⁴⁴ J. W. Gregory: The rift valleys and geology of East Africa. An account of the origin and history of the rift valleys of East Africa and their relation to the contemporary earth-movements which transformed the geography of the world. London, 1921.

⁴⁵ E. Krenkel: Die Bruchzonen Ostafrikas. Berlin, 1922.

to about the close of the Cretaceous, when the trough and its eastern borderland were almost completely broken up and faulted into the depths of the Indian Ocean.

Graben are also downfaulted areas, but of much smaller dimensions. They may develop on any part of a folded land.

FOUNDERING OF BORDERLANDS

The borderlands of North America are pictured in figures 2 and 3. These show that North America in Proterozoic time was 2,000,000 square miles larger than it is now, and that Appalachia in the Devonian extended not less than 250 miles beyond the present shoreline. Now the eastern part of this land is warped at least 5,000 feet into the depths of the Atlantic. On the other side of North America the outer parts of Cascadia have been warped and probably in the main faulted into the Pacific to depths of 14,000 feet.

During the Paleozoic and the earlier half of Mesozoic time the west coast of South America appears to have extended at least several hundred miles beyond the present shoreline, and some of this old land remains along the coast of Chile. Off Peru the Andes borderland has gone into the abyss anywhere between 13,000 and 24,800 feet, and this seemingly since middle Pliocene times. While this foundering was going on, the peneplaned Andes were raised vertically not less than 10,000 feet, a differential movement between the elevated and depressed masses amounting to nearly 7 miles.

FOUNDERRINGS OF CONTINENTS

It is now widely admitted that Madagascar, an island of 230,000 square miles area, was once a part of Africa, and yet today it is separated from the latter by Mozambique Channel, from 240 to 600 miles wide, with depths down to 11,800 feet. Madagascar is, however, only the southern end of far greater Lemuria, a land of Mesozoic and older times that extended northeasterly, taking in all of peninsular India. Of this continent, there is left Madagascar, India, and groups of islands (Seychelles, Comoro, etcetera), with oceanic depths between them varying from 13,650 to 17,380 feet.

The greatest of all foundered continents, however, is the ancient Mesozoic land named by Neumayr Sino-Australia, embracing southeastern China and Siam, Sumatra, Java, Borneo, Celebes, the Philippines, New Guinea, Australia, New Zealand, New Caledonia, the lesser Hebrides, the Solomons, Fijis, and Samoas. Great areas of Sino-Australia have gone into depths variable between 10,000 and 13,000 feet and in places to over

17,000 feet. The foundered areas are parts or the whole of mesogeosynclines and synclinoria and of geanticlines and anticlinoria. Abendanon has renamed Sino-Australia Aeguinoctia.

The history of this foundering is still largely unknown. It probably began in the later Paleozoic, was most active in the later Mesozoic when Australia was separated from Asia, and these negative and positive movements have continued through Cenozoic time into the present. In most places along the margins of the continents facing the Pacific we note these great founderings, and the largest of all in the South Pacific. The chief area of crustal subsidence is, of course, in the water hemisphere, and it may well be that the united pull of the subsiding Antarctic and South Pacific oceans was the cause for the breaking up of Sino-Australia. The inbreaking of the Indian Ocean at the expense of Lemuria and greater Australia was probably also in sympathetic connection with this negative movement of the Antarctic Ocean.

In the Atlantic Ocean there is nothing comparable to this foundering of the Pacific. The relations are rather with the type of foundering in the Indian Ocean. Western Gondwanaland, uniting Africa to Brazil, was not in existence after Lower Cretaceous times, though there is much marine faunal evidence back of the latest Jurassic down to the Silurian, proving the existence of a land across the equatorial Atlantic. The foundering in the Atlantic began about the same time as that in the Indian, and all of it appears to have been in sympathetic connection with the vast subsidence in the water hemisphere.

SUMMATION AND CONCLUSIONS

My paleogeographic studies have confirmed the well-known fact that the vast medial region of the North American continent, while slightly positive, is in reality neutral in regard to sealevel. It is the "nucleus," or "Kratogen," of the continent, taking in the greater part of eastern Canada and most of Greenland (see map, figure 3). This very ancient land, in its rocks and structure, is seemingly in the main of Archeozoic making, but during much of Proterozoic time was still undergoing orogeny. Since the late Ordovician the neutral region has been a lowland.

The great neutral area of Canada is continued southwestward across the region known as Siouia into greater Mexico. It can therefore be definitely stated that Siouia and especially the Canadian shield have ever since the Cambrian furnished but little clastic sediment to the seas. Western Mexico and Siouia, on the other hand, were during the Mesozoic highlands furnishing sediments in great volume to the adjacent seas.

Walcott long ago pointed out that the *North American continent is very old*, that it was not only outlined in late Proterozoic time, but that it was larger then than it is now. We now see that this continent had its present configuration even early in Proterozoic time, when it appears to have been 2,000,000 square miles larger than it is to-day.

While the neutral area is wholly devoid of post-Proterozoic geosynclines, yet it was four times in the early Paleozoic widely covered by independent Arctic floods (see maps, figures 6 and 7). These spread southward across the nucleus into southern Canada, where their waters united with seas coming north through the Mississippi Valley. The first one was of middle Ordovician (Black River-Trenton), and the second of late Ordovician (Richmondian) time. The other two were of the early and middle Silurian (Alexandrian and Niagaran). In the north the combined depth of their marine sediments, largely limestones, may attain to 3,000 feet, while in southern Canada they appear to be measured by a few hundred feet. These floods, in continuation with the Franklinian trough, had nothing to do with those of the Cordilleran geosyncline, and their waters may or may not have been in communication with that trough.

Now let us consider the borderlands (see map, figure 3). The northeastern portion of North America was margined by *Acadia*, of which there remains more visible than of any of the other borderlands. It was a marked diastrophic region from early Cambrian time to the close of the Pennsylvanian, though its marine history is practically pre-Carboniferous. To the south of it lay *Appalachia*, which seemingly continued unbroken into greater *Antillia*. Appalachia was in periodic crustal unrest throughout the Paleozoic, and attained its maximum compression during the Permian. Shortly afterward, in the Triassic, this borderland began to fracture and to develop a block mountain structure, and the greater eastern part of it went under the Atlantic during middle Mesozoic time. With its foundering, southern Antillia began to develop a marine history, and with the close of the Mesozoic and ever since, this southern borderland has been in the throes of crustal unrest.

The Arctic side of North America was margined by the borderland *Pearya*. It was in existence as a highland certainly in Upper Cambrian time, and again in the late Devonian. Just when its orogenic history ceased is not yet clear, but seemingly during the Permian.

The whole of western North America south of Alaska was margined by greater *Cascadia*. It was present in early Proterozoic time as a highland, and again during the Cambrian. It was folded, locally, in northern California, during the Middle Devonian. In the Pennsylvanian or earlier

it divided into two northwesterly-southeasterly trending lands, a northern mass, the *Charlotte borderland*, which endured, though greatly reduced in area, into early Cenozoic time, and a southern one, the *Californian borderland*, which suffered marked orogeny throughout Mesozoic and Cenozoic times. At present, much of Cascadia is faulted into the great depths of the Pacific.

We have now recounted the most positive and the least positive areas of the North American continent, and next we must bring together a brief statement as to the various geanticlines (see map, figure 2). The oldest of these is the *New Brunswick geanticline*, dividing Acadia into two geosynclinals. This periodically rising axis had its origin at the close of the Proterozoic, and late in Devonian time it became so positive and so beset with active volcanoes as to blot out the seas on either side of it. Even though the earliest Carboniferous seas partially reentered between these mountains and formed the *Northumberland embayment*, yet this orogenic province continued positive till the close of Pennsylvanian time.

The next geanticline to appear arose out of the medial area of the greater Mississippian sea and divided it into two basins after early Silurian times. This was the well known *Cincinnati geanticline*. It was at no time during the later Paleozoic a very positive axis of uplift.

During the later Pennsylvanian, there was much orogeny throughout the borderlands of eastern North America, and to a far more limited extent in Texas and Oklahoma. In keeping with this mountain-making, the western area of neutral Siouia also began to rise vertically. This is the *Ancestral Rocky Mountains geanticline*, whose rising finally completely blotted out in the area of Siouia the later Paleozoic seas. The geanticline was, however, reduced to sealevel before the Upper Jurassic, since the seas of this time and those of the Cretaceous again completely transgressed all of it. This old structure was reelevated by the Laramide orogeny and by the epeirogeny of late Cenozoic times.

The most interesting of all the positive areas is the well known *Cordilleran Intermontane geanticline* (see maps, figures 2 and 16). This made its appearance through warping late in the Triassic as a low arch throughout the States of Arizona, Nevada, Utah, and Idaho, and then in the earlier Jurassic the arching was continued northward into British Columbia. It was completed by the Nevadan orogeny of late Jurassic time, which established it during the Cretaceous throughout the extent of North America. It was a geanticline of the first order, and was a vigorously rising mass during the Cretaceous. During its growth it blotted out much of the Paleozoic Cordilleran seas, and along its eastern

side throughout the whole extent of the geanticline, from Siberia to the Caribbean, there developed the vast Rocky Mountain geosyncline. Structurally, it remade the western portion of the continent into a bilateral system of mountains, the mighty Cordillera of North America.

We will next consider the geosynclines (see map, figure 3). It was between the great medial or neutral region and the much smaller borderlands that three of the four *primary geosynclines* were developed, namely, the small Arctic Franklinian trough and the better known Appalachian and Cordilleran geosynclines. Their greatest subsidence was toward the borderlands. Out of the Cordilleran primary geosyncline came the Pacific and Rocky Mountain *sequent geosynclines* (see map, figure 16). The small Acadian primary geosyncline, on the other hand, lies between the borderland Novascotica and the New Brunswick geanticline (see map, figure 3).

The *Cordilleran geosyncline* is the oldest and has had the greatest amount of crustal evolution. A very small western part of it is still seen as a marine waterway in the Great Valley of California. This long-enduring geosyncline had its origin early in the Proterozoic, and during this era its maximum subsidence appears to have been about 30,000 feet. Curiously, no orogeny developed within the geosyncline at the close of the Proterozoic, but its borderland Cascadia was then reelevated into a highland, since the following Cambrian sedimentation alone was as much as 15,000 feet. Then there was no striking crustal change until early in Pennsylvanian time, when the Mackenzie shoreline was warped some hundreds of miles to the west, and the geosyncline consequently took on a northwest-southeast trend. We have seen that the Ancestral Rocky Mountains geanticline during Permian and Triassic times also pushed the eastern shoreline of this geosyncline something like 600 miles to the west. After the middle Triassic, the trough was greatly restricted, and with the subsequent rising of the Cordilleran geanticline, this great trough early in the Lower Cretaceous became the comparatively narrow sequent *Pacific geosyncline*. On the other hand, the rising of this geanticline is evidenced in the trough by marked volcanic activity, beginning in the late Pennsylvanian and attaining its climax in early and middle Triassic times. With the maximal rising of the geanticline late in the Jurassic, its area was to a large extent invaded by vast bathyliths and by renewed volcanic activity, the extrusive materials being also present in considerable volume in the Lower Cretaceous strata of the Pacific geosyncline. Then toward the close of the Cretaceous, the British Columbia part of the Pacific geosyncline became land. The Californian trough, however,

continued as a marine area, although greatly restricted, not only throughout the Mesozoic, but the Cenozoic as well.

With the rising of the Cordilleran Intermontane geanticline, there came into existence the eastern sequent and short-lived but very mobile *Rocky Mountain geosyncline*. This subsidence appeared first in Mexico, beginning possibly early in the Permian and certainly in the late Triassic, and spread northward into Kansas by the close of Lower Cretaceous time, when the Mackenzie end of the trough also had marine waters as far south as central Alberta. Then early in the Upper Cretaceous the whole of the geosyncline was one vast inland sea. The western geanticline again began to rise late in the Cretaceous, and apparently the whole of the arch from southern Mexico north into Alberta was then studded with active volcanoes. With this further rising of the arch, the Rocky Mountain seas were converted into land during the close of the Cretaceous. The present high altitude of the Cordillera, however, came with the vast epeirogeny that began in the middle Miocene and was completed toward the close of the Pliocene.

The *Appalachian geosyncline* made its reappearance south of Virginia in earliest Cambrian time, but long before the close of the Lower Cambrian it was in clear evidence from Alabama to Labrador. This is the type geosyncline (see map, figure 4). The northern half, or the *Saint Lawrence trough*, was blotted out by the orogeny of late Devonian time, and the whole of the Appalachian geosyncline was converted into mountains during the Permian. East of the southern half of this geosyncline was the borderland Appalachia. Southeast of the Saint Lawrence trough and the New Brunswick geanticline was the *Acadian geosyncline*, and both troughs were elevated above sealevel by the Devonian orogeny (see maps, figures 7 and 9). Therefore we may say that the northern Appalachian system of mountains are bilaterally symmetrical structures, while the southern Appalachians, even though they are polygenetic mountains, are wholly a one-sided system folded and thrust away from the Atlantic Ocean.

To the northwest of Greenland is the *Franklinian geosyncline*, bounded on its Arctic side by the borderland Pearya, while its deposits thinned inland across the Canadian shield (see maps, figures 3 and 5). The presence of this geosyncline is clearly evidenced in late Cambrian time, and we suspect that it came into existence with the diastrophism of the late Proterozoic. During the Paleozoic, the Franklinian trough subsided something like 20,000 feet, and appears to have been blotted out by the orogeny of Permian times.

Of embayments, there are four. (1) With the vanishing of the Saint Lawrence and Acadian troughs in Devonian time, there appeared in greater Acadia the *Northumberland embayment*, extending across the Maritime Provinces of Canada and Newfoundland (see maps, figures 10 and 11). It endured during the Mississippian and Pennsylvanian periods, the subsidence nowhere exceeding 18,000 feet. The embayment ceased with the Permian orogeny.

(2) Chiefly in Arkansas and Oklahoma, from Upper Cambrian to Middle Pennsylvanian time there was developing the *Ouachita embayment*, an east-west trough connecting more or less directly with the Appalachian geosyncline (see maps, figures 3 and 6). It subsided markedly during its earliest existence but more especially during the Pennsylvanian, since in Arkansas the maximum of depression appears to have been 35,000 feet. The trough failed as such with the Pennsylvanian orogeny.

(3) Another west-east trough was the *Sonoran embayment* of north-western Mexico, which was more or less closely connected with the Cordilleran geosyncline (see maps, figures 3 and 6). It reappeared in the Upper Cambrian and endured into the Pennsylvanian, during which time the trough sank something like 15,000 feet.

(4) The fourth of these basins was the *Alexandrian embayment* of southeastern Alaska, which finally merged with the Pacific geosyncline during the Pennsylvanian (see map, figure 3). It came into being at least as early as the Lower Ordovician, and during its existence the basin sank not less than 12,000 feet.

It does not follow that when the geosynclines are in flood the neutral areas are at the same time more or less under water. Frequently the floodings are restricted to the geosyncline, and at other times the Arctic floods cover essentially the neutral areas of the continents. In the same way, the Mississippian seas west of the Cincinnati geanticline may be in evidence when the Appalachian geosyncline is dry.

It appears from the irregularity of the continental floodings that their presence is primarily due to crustal movements, but it does not at all follow that all are so brought about. The widespread and more or less cosmopolitan faunas of the Upper Cambrian, Middle Ordovician, Silurian, Devonian, and late Cretaceous appear to bear out Suess' hypothesis of eustatic (= world wide) higher marine levels, when the continents are base-leveled and the oceans most filled with sediments, causing them to spill widely over the lands. Clearly, every grain of sand displaces just as much water.

As to the time of origin of the primary geosynclines, we may say that all arose in the Proterozoic (see map, figure 1), and that out of the Cor-

dillieran one there developed in Mesozoic time two sequent geosynclines (see map, figure 16). The amount of sediment in any of these troughs appears to have nothing to do with the time when they were folded into synclinoria. In places there may be even less than 10,000 feet of sediments, on the average the amount of subsidence is between 15,000 and 35,000 feet, while in the mid-length and width of the combined Cordilleran-Rocky Mountain geosynclines there was about 76,000 feet, or about 14 miles depth, of strata before the troughs evolved into synclinorial mountains. Nor has the length of geologic time anything to do with the vanishing of the geosynclines. Both the Saint Lawrence and the Acadian troughs endured only from early Cambrian time to the close of the Devonian; the southern Appalachian one was in formation from the early Cambrian into the Pennsylvanian; while vast stretches of the Cordilleran geosyncline did not fold from early Proterozoic time until the close of the Cretaceous, even though other parts of the trough rose into a very long and high geanticline during the middle Mesozoic. In all of this, we appear to see that the balancing of masses under the law of isostasy continues until some other force changes the relations of things deep down within the lithosphere.

So far as North America is concerned, we see that no primary geosynclines have come into existence after the Cambrian, and that the larger ones were clearly established either late or early in the Proterozoic. Sequent geosynclines, of as great importance as any (Rocky Mountain), along with vast geanticlines (Cordilleran Intermontane), originated in Mesozoic time, but their evolution was out of a very wide and primary geosyncline (Cordilleran). We therefore conclude that in North America no new deeply subsiding areas have originated since the early Proterozoic.

It may be that the present highly elevated condition of the Cordilleran Intermontane geanticline will subside some thousands of feet. Should this happen, it appears probable that an inland sea will form, extending the Gulf of Lower California into the Great Basin country. It will be, however, a rift sea like the present Red Sea, formed through the in-breaking of the Cordilleran Intermontane geanticline, and not a new geosyncline.

The narrower and shorter-lived geosynclines (= monogeosynclines), seemingly conditioned by the smaller Atlantic and Arctic oceans, are in striking contrast to the far wider, longer-enduring, and immensely more diastrophically active geosynclines (= polygeosynclines) conditioned by the Pacific. We therefore ask, Has the vastness of the negative areas, the oceans, any direct and sympathetic action upon the sides of the positive continents? It would seem so. If this surmise is admitted, we must

next ask the even more significant question, Why is it that western North America, in direct contact with the greatest ocean, exhibits but little orogeny until Jurassic time? We have seen that in eastern North America, mountain-making was very active in late Devonian and again in Permian times; in Europe at the close of the Silurian and several times during the Carboniferous. Do these facts, then, mean that the North Atlantic (= Poseidon) was an actively sinking ocean during the Paleozoic, while the North Pacific was not a markedly subsiding area until early Mesozoic time?

In further elaboration of these surmises, we note the greater volume of the sediments of the Appalachian, Acadian, and Franklinian geosynclines, when contrasted for each period with those of the Cordilleran trough, which shows that the borderland Cascadia was less often reelevated than were the eastern borderlands Appalachia and Acadia. On the other hand, in western North America, from Alberta south to Nevada, the greater part of the Ordovician and most of the Silurian are poorly represented by sediments, again showing that the Atlantic was diastrophically active earlier than the Pacific. We may therefore speak of Atlantic and Pacific types of geosynclines, since the same relations of parts are also true for South America.

We must also ask ourselves, Why are there periodically rising borderlands with geosynclines along their inner sides? They appear to be the compensating areas of subcrustal flowage between the subsiding oceans and the unmoved or horst-like neutral areas or "Kratogens" of the positive continents.

We will now consider the mesogeosynclines. It has been shown that all of the geosynclines of North America form on the inner sides of borderlands which are but the diastrophically active margins of the continent. Furthermore, that geosynclines are destined to evolve into mountains. This is the American theory of geosynclines, and it is in direct opposition to the views of European geologists, especially as formulated by Haug in 1900. The fundamental difference between the two theories is that Haug places the geosynclines on the outer sides of the continents in the areas of the continental shelves (figure 18). His studies center in the history of Tethys, the greater Mediterranean, once extending from the Atlantic to the Pacific. This is a very deep and vast basin of the oceanic type, situated, however, between close-lying continents. Tethys was not, therefore, a geosyncline in the American sense, but a mediterranean or mesogeosyncline.

To extend the meaning of the term geosyncline to all subsiding areas of sedimentary accumulation, to mediterranean and even to oceanic

basins, as was done, it is true, for the first time by Dana, is to befog the brilliant idea of James Hall. Our understanding of geosynclines (both monogeosynclines and polygeosynclines) is that they are variably long and variably wide, very mobile, sinking areas that always originate within a continent; they are more or less long in geologic development, and receive great quantities of sediments derived in the main from the borderlands. The more rapidly sinking side of a geosyncline is adjacent to the inner side of a borderland, while the subsidence of the trough becomes less and less toward the neutral area of the continent. Finally, when orogenic forces have converted the geosyncline into synclinal mountains, these either are the inner portion of the anticlinal borderlands, or they occur on one or both sides of geanticlines.

Mediterraneans are vastly greater fields of diastrophism, with the longest and most intricate of geologic histories. Of ancient Tethys, the western end still persists as the Roman Mediterranean, with depths down to 14,700 feet. Contrast these ocean-like basins with the shallow-water geosynclines, whose average depth is several hundred feet, and it becomes plain that the two types of marine waters can not be grouped together under one term.

We have seen that all the geosynclines of North America have become dry land and mountainous. Into what are the mediterraneans evolving? We know that Tethys, formerly extending from Asia Minor to Burma, has been converted during the Cenozoic into dry mountainous land across 5,000 miles. Seemingly the whole of the Roman Mediterranean is destined to the same end, but eastern Tethys throughout the length of the Dutch East Indies is in the main foundering with its mountains permanently into the oceanic depths. The American mediterranean is to a lesser extent doing the same, since Antillia is breaking down into the Caribbean and the Atlantic.

It appears that once a region is folded through lateral pressure, it rarely redevelops a geosyncline. This is most easily seen in the Atlantic type of troughs, since neither the Appalachian, Acadian, or Franklinian geosyncline has gone through even a partial second cycle of geosynclinal formation. On the other hand, the "Kratogens," once the area of the most ancient geosynclines, may, after they are peneplained, be widely flooded by epeiric seas. This was the case with the Canadian shield, and the roots of the Paleozoic Alps of Europe have been widely transgressed by Mesozoic seas. These floods are, however, not those of geosynclines. Nor do geanticlines or borderlands develop geosynclines. Therefore it may be assumed that a region once folded and made positive, becomes stiff and resistant, and that, as a rule, it will remain so throughout time.

On the other hand, the borderlands and Sino-Australia have foundered more or less into the oceans. In fact, even the Archeozoic and Proterozoic synclinoria of the Canadian shield or kratogen have not undergone a second cycle of localized subsidence. However, a region once made positive through orogeny will subsequently be arched from time to time, and the aggregate of these epeirogenic uplifts may attain several thousand feet, as in the Appalachians (2,000) or the Rocky Mountains (7,000), or 10,000 feet as in the normally faulted rising masses of the Andes. We have also seen that out of the Cordilleran geosyncline there arose the Intermontane geanticline, while the sequent geosynclines on either side of it are the folded parts of the former greater trough.

Diastrophism is mainly due to earth shrinkage. My paleogeographic studies appear to make it clear that there are at least five sets of interactions bringing on the marine floods over the continent and the making of mountains. Three of these are in consequence of earth shrinkage, and one is due to crustal or isostatic adjustment. All of them are reflected in the marine transgressions and emergences. The sealevel is, in addition, altered by the filling of the seas and oceans with the debris of the lands, by the subtraction of oceanic water and the piling of it upon the lands during glacial times, by the growth of mountains of extrusion, and by the movements within the oceanic basins themselves. It is not easy for stratigraphers to evaluate properly the significance of these oceanic alterations in their relations to continental floodings, and we may eventually come to see that their importance is far greater than is now believed.

Taking Le Conte's views of 1897 and modernizing them, we hold that of crustal movements there are four categories, as follows:

(1) The most primitive, extensive, and longest-enduring progressive movements are those of (*a*) negative or downward direction, resulting in the oceanic depressions with the heavier kinds of rocks; and (*b*) positive or upward direction, giving rise to the continental platforms of lighter materials.

(2) The comparatively quick orogenic progressive movements in one general direction due to crustal lateral thrusting. They give rise in the stratosphere (or tectonosphere, Sonder 1922) to the folded mountains (orogeny), and in compensating areas to stretching and rifting (tafro-geny). Earth shrinkage is concentrated in the main upon the geosynclinal areas, the lines of greatest weakness in the crust.

(3) The slowly forming epeirogenic or more or less wide and high arching or vertical movements of an oscillating character, now upward and now downward. Epeirogenesis predicates eventual orogenesis.

(4) The isostatic oscillatory movements in compensation for transfer of load from one place to another; areas of sedimentation tend to sink, and eroding ones rise. Isostasy is an important cause of crustal movement, but is of secondary import to those produced by earth shrinkage.

If we agree with T. C. Chamberlin that the earth since its growth out of planetesimals born of the sun has shrunk 570 miles radially, we see here the primal causation for the wonderful cyclic reelevation of the lands and sinking of the oceans, and much of the consequent periodic changes in climate.

That the earth, under any theory of earth origin, is a shrinking mass, is shown mainly by the periodic folding of the lithosphere into mountain ranges, and by the subsidence of the oceanic areas. The crustal shortening is further evidenced in the long-continued recurring times of epeirogenic warping movements that culminate in the quicker orogenic ones. This crustal shortening, due to radial shrinking, follows upon the loss of interior heat, magmatic alteration, and extrusion of lavas, ashes, water, and gases, and mainly through molecular rearrangement of the centrosphere engendered by the continuous attraction pressure. With Kober, we therefore say that "shrinking of the earth is no longer hypothesis nor theory, on the contrary it is knowledge built on ascertained facts."

This periodicity, moreover, leads to the most extraordinary result of all, namely, to times of quickened organic evolution and the pulsing of life, to the peopling of the lands by the denizens of the oceans, an evolution that somewhere and somehow has tended to make it possible for the algæ of the seas to feed on the air and to clothe the land with verdure; the latter in turn yields food for the animals forced to emerge from the realm of Neptune, and thus life progresses dominantly upward until it results in reasoning man, the controlling organism of the Psychozoic era.

My labor of love is now finished. I have told you in the main of the localized geosynclines and the oceanic floodings of the continent. In the following papers of this Symposium you will learn more of how geosynclines are transformed into synclinorial mountain systems, or how vast expanses of inland seas become transformed into glorious mountains, areas scenically grand, geologically most difficult, and structurally highly interesting and significant. From studies in depression I turn you over to studies in uplift.

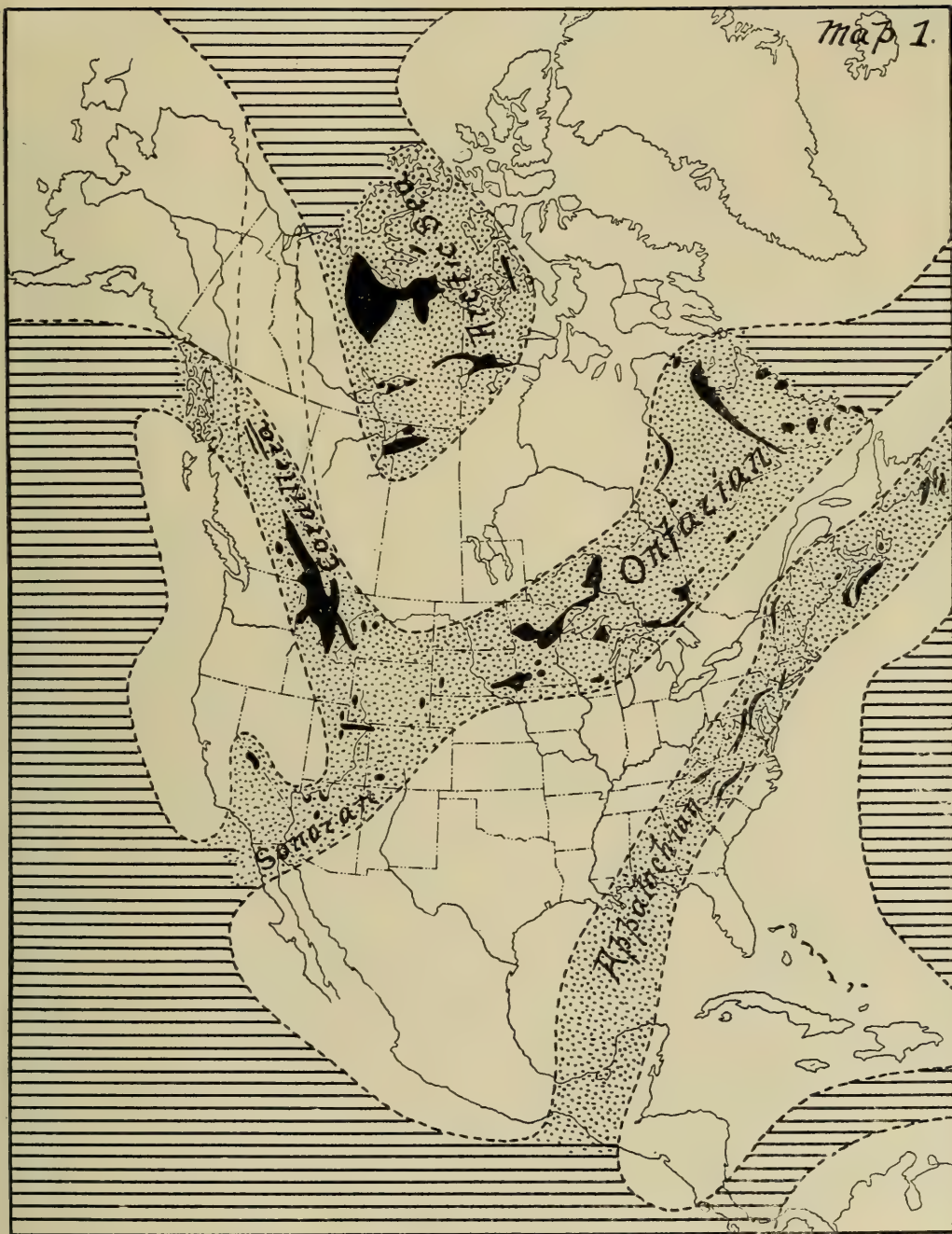


FIGURE 1.—*Geosynclines (dotted), Lands (white), and Oceans or Mediterraneans (ruled) during late Proterozoic Time*

Black marks the known outcrops of Animikian, Keweenawan, Beltian, etcetera.
The Cordilleran trough may have opened into the Arctic Ocean.

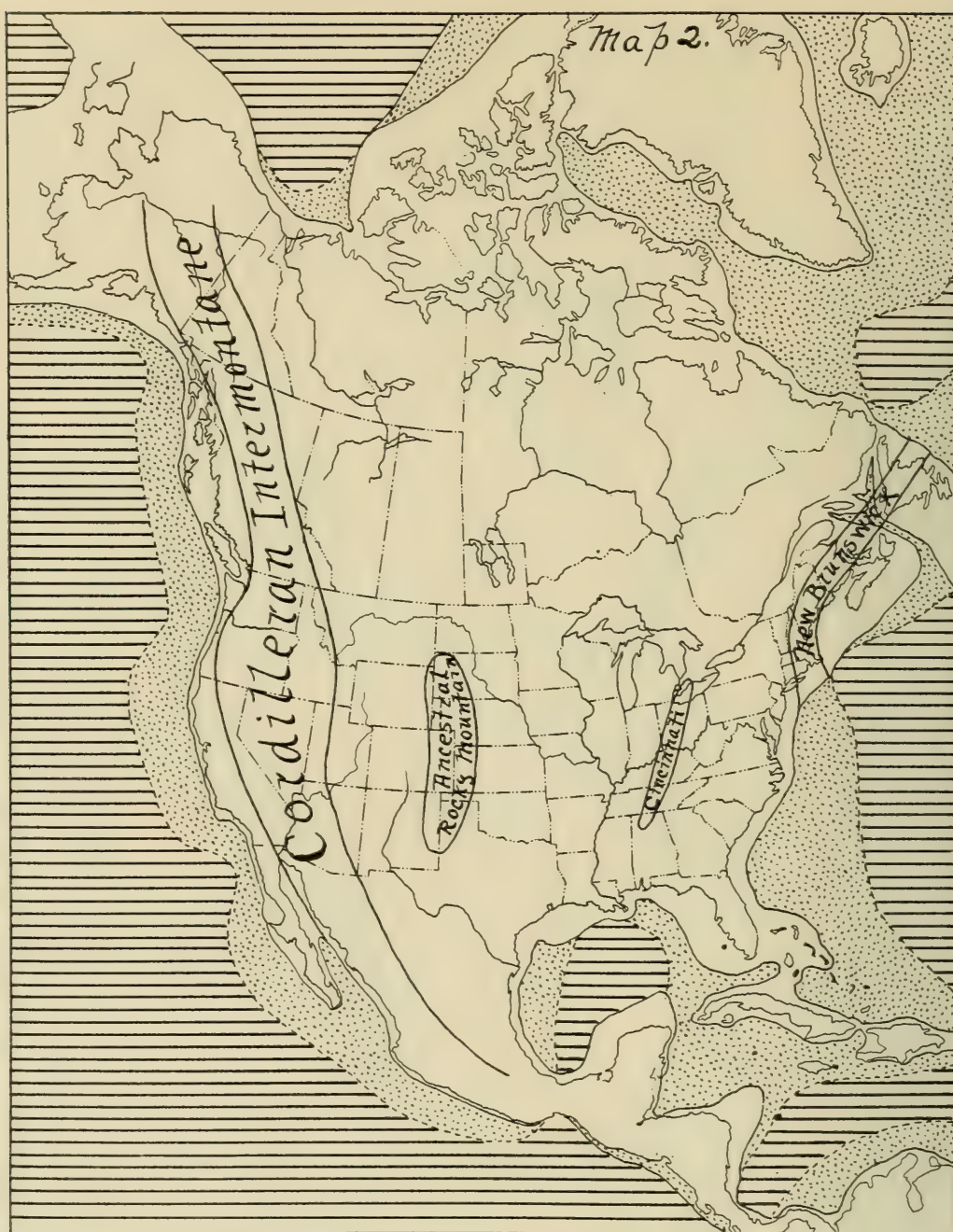


FIGURE 2.—North America in early Proterozoic Time

Dotted spaces indicate the lands since foundered into the oceans. The positions of four geanticlines of later eras are also shown.

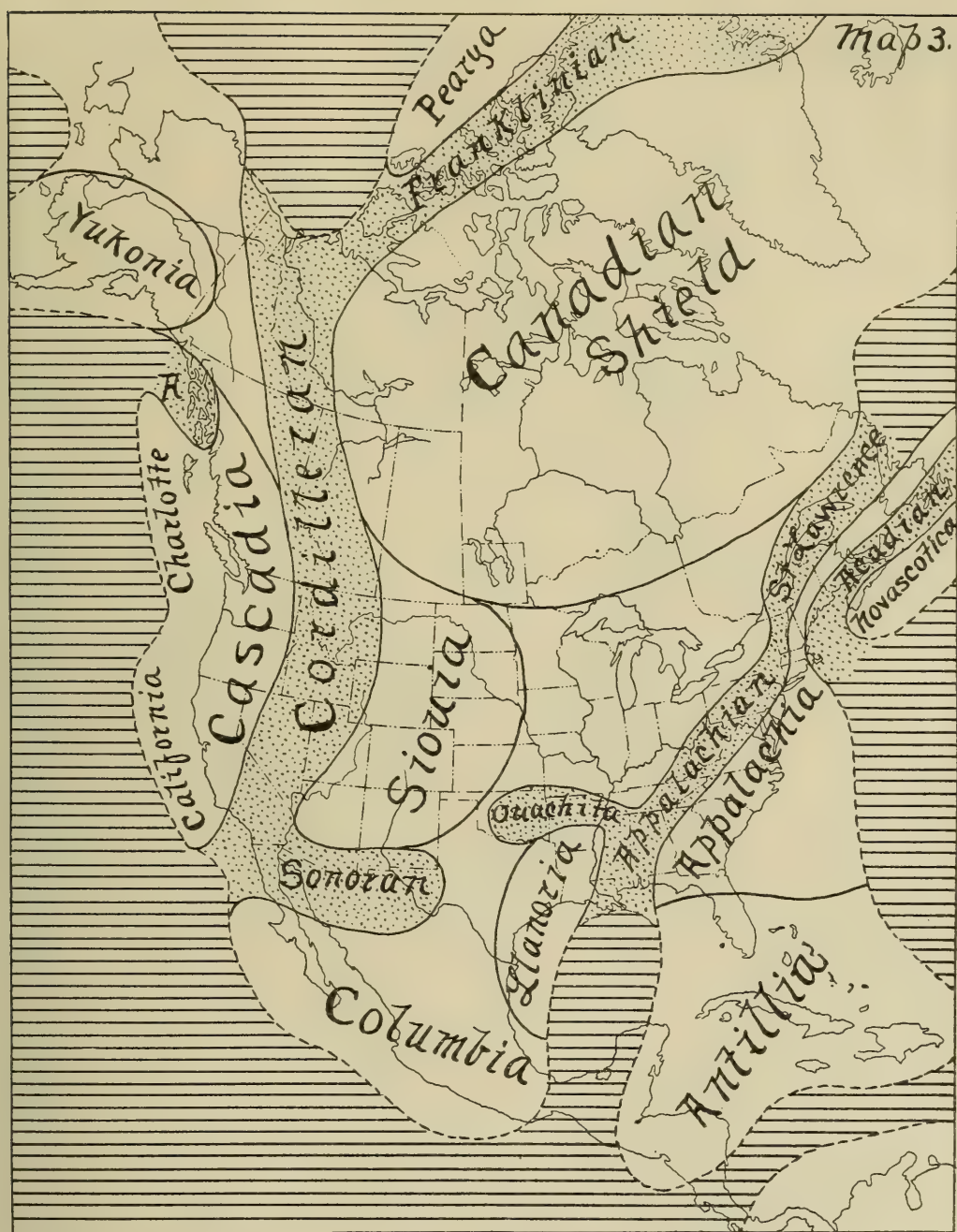


FIGURE 3.—*Borderlands (white), Geosynclines and Embayments (dotted), and neutral Areas (the great central Region between Geosynclines) of Paleozoic Time*

A = Alexandrian embayment.

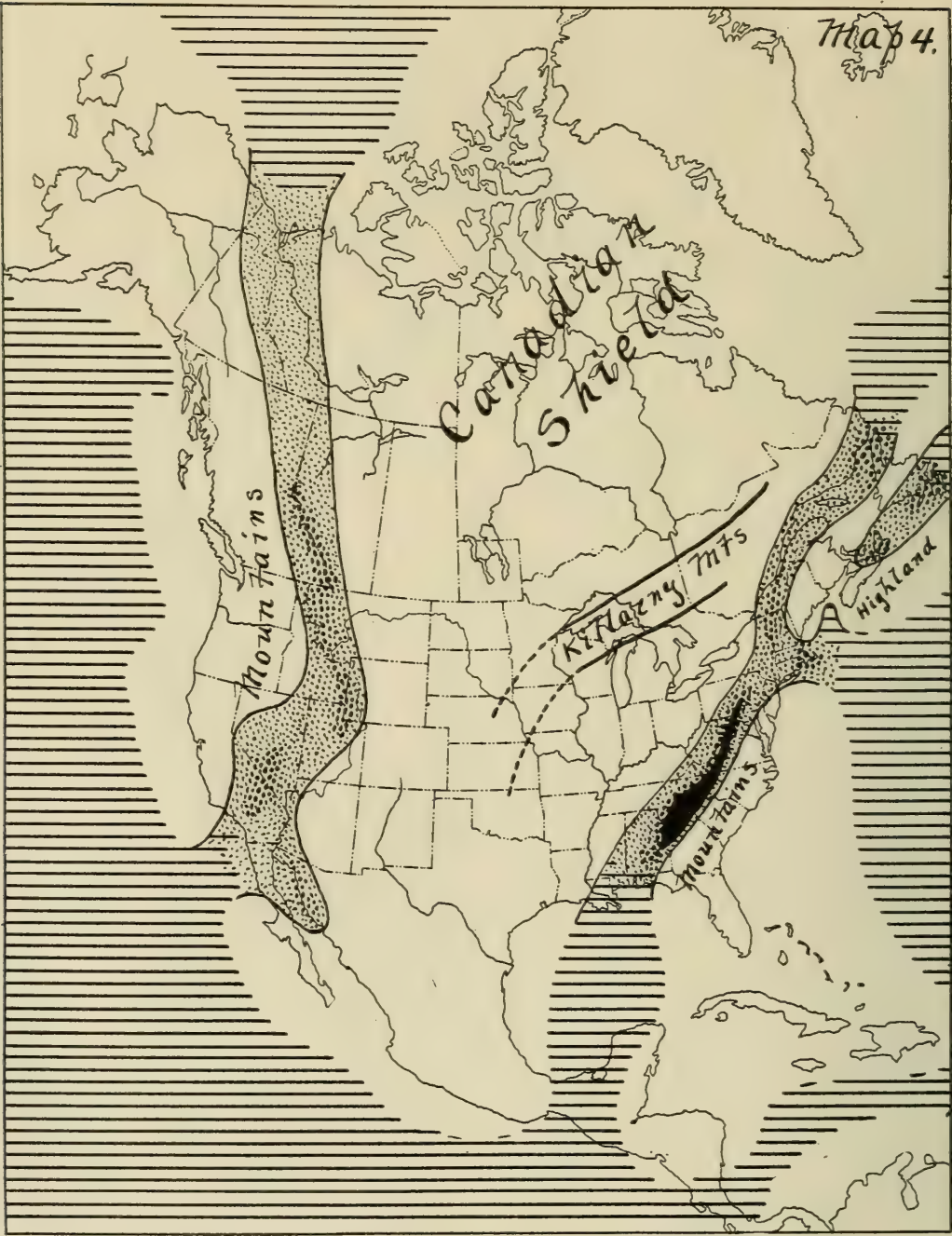


FIGURE 4.—Geosynclines of late Lower Cambrian Time

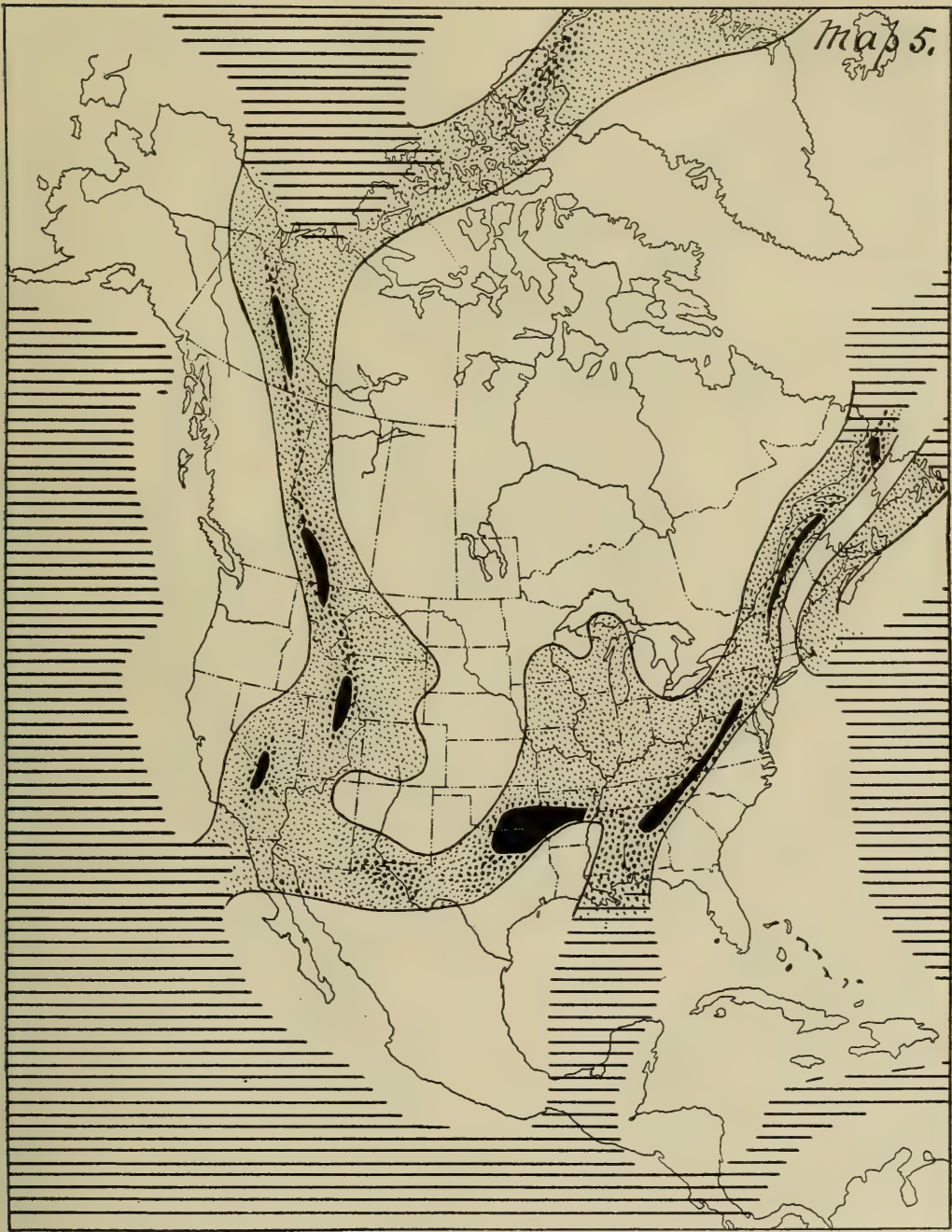


FIGURE 5.—*Geosynclines and their Extensions of Upper Cambrian and Canadian Time*

Intensity of shading indicates areas of greatest subsidence.

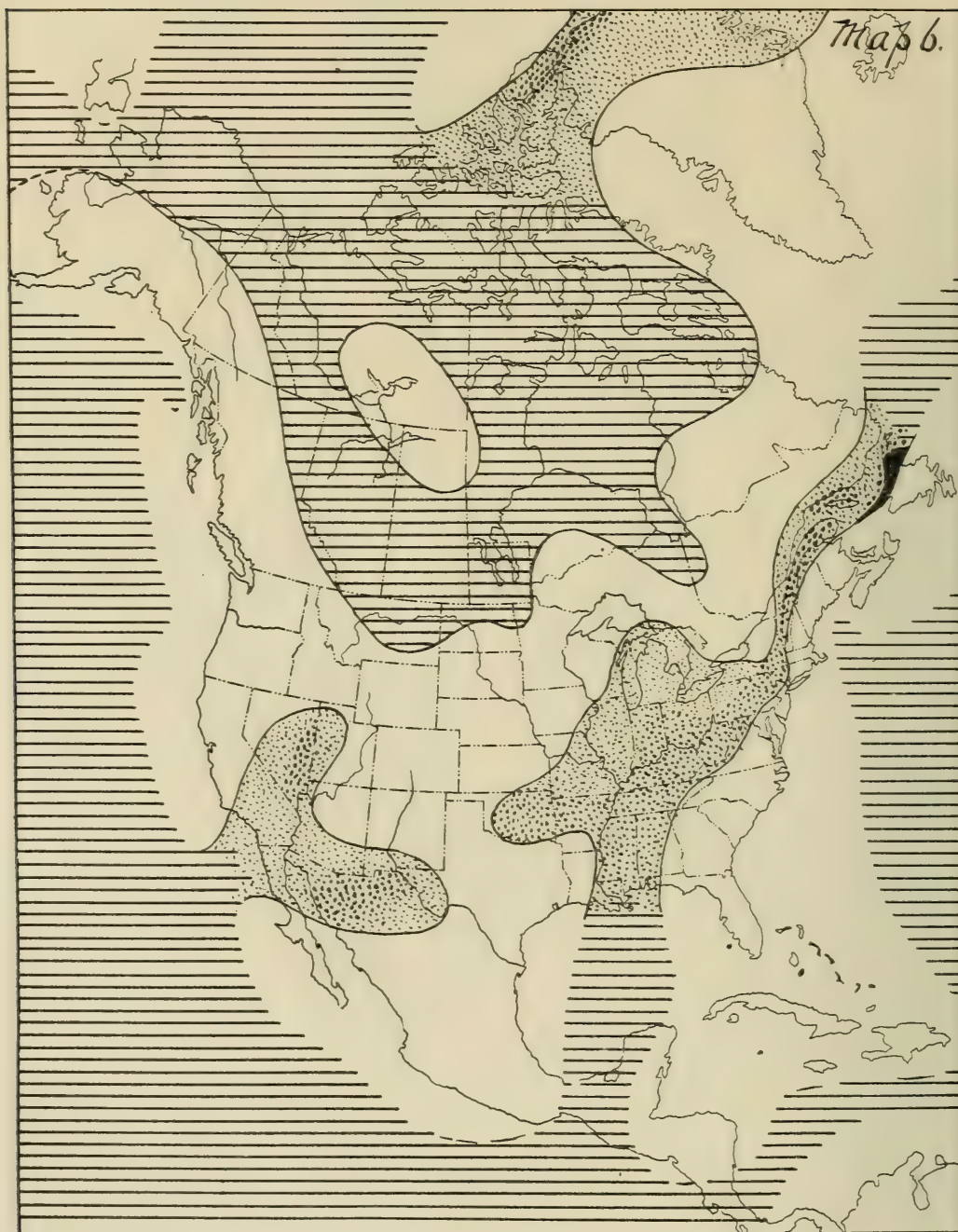


FIGURE 6.—*Geosynclines and Embayments (dotted) and Arctic Sea (ruled) of Ordovician Time*

Intensity of shading indicates areas of greatest subsidence.

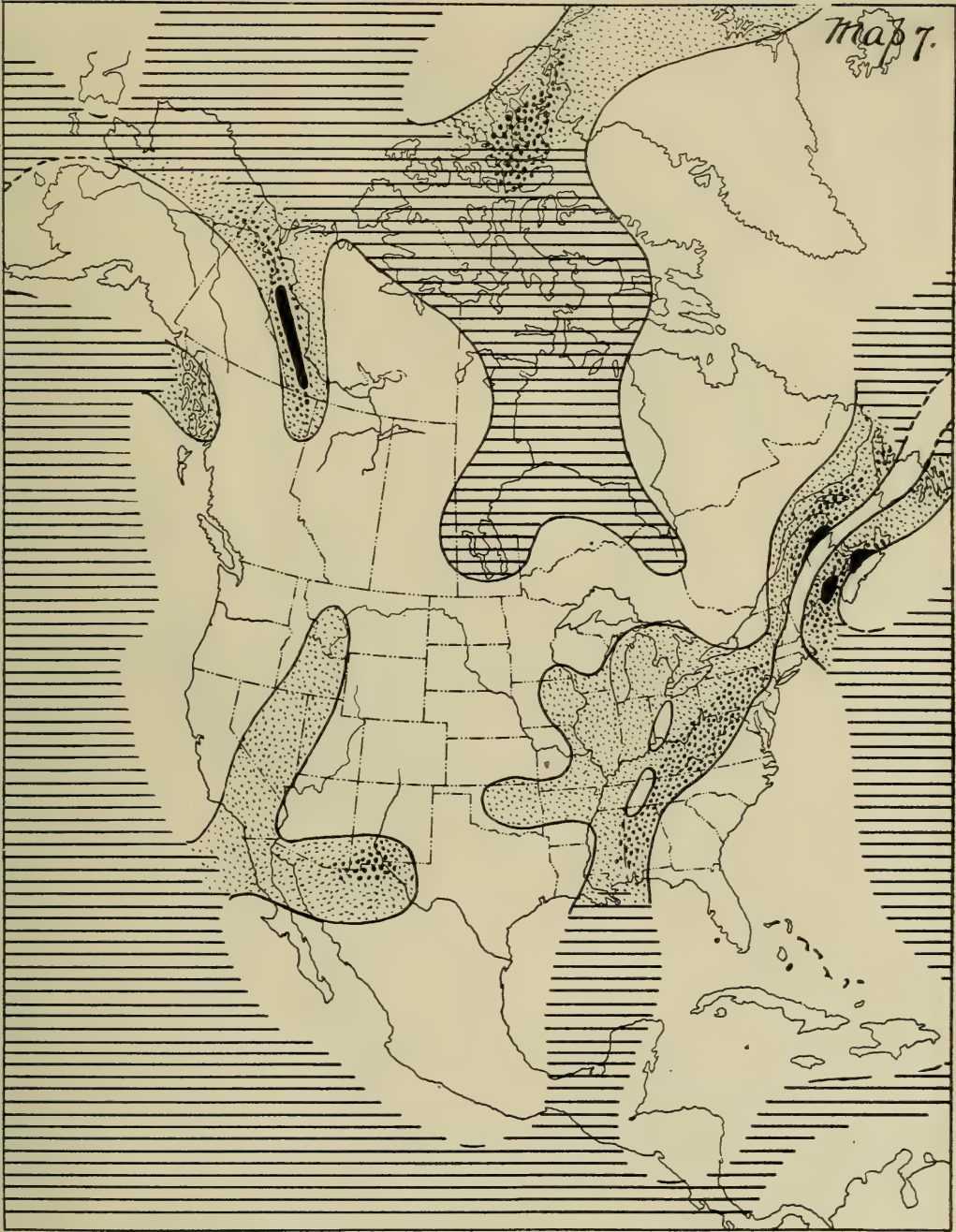


FIGURE 7.—Geosynclines and Embayments (dotted) and Arctic Sea (ruled) of Silurian Time

Intensity of shading indicates areas of greatest subsidence.

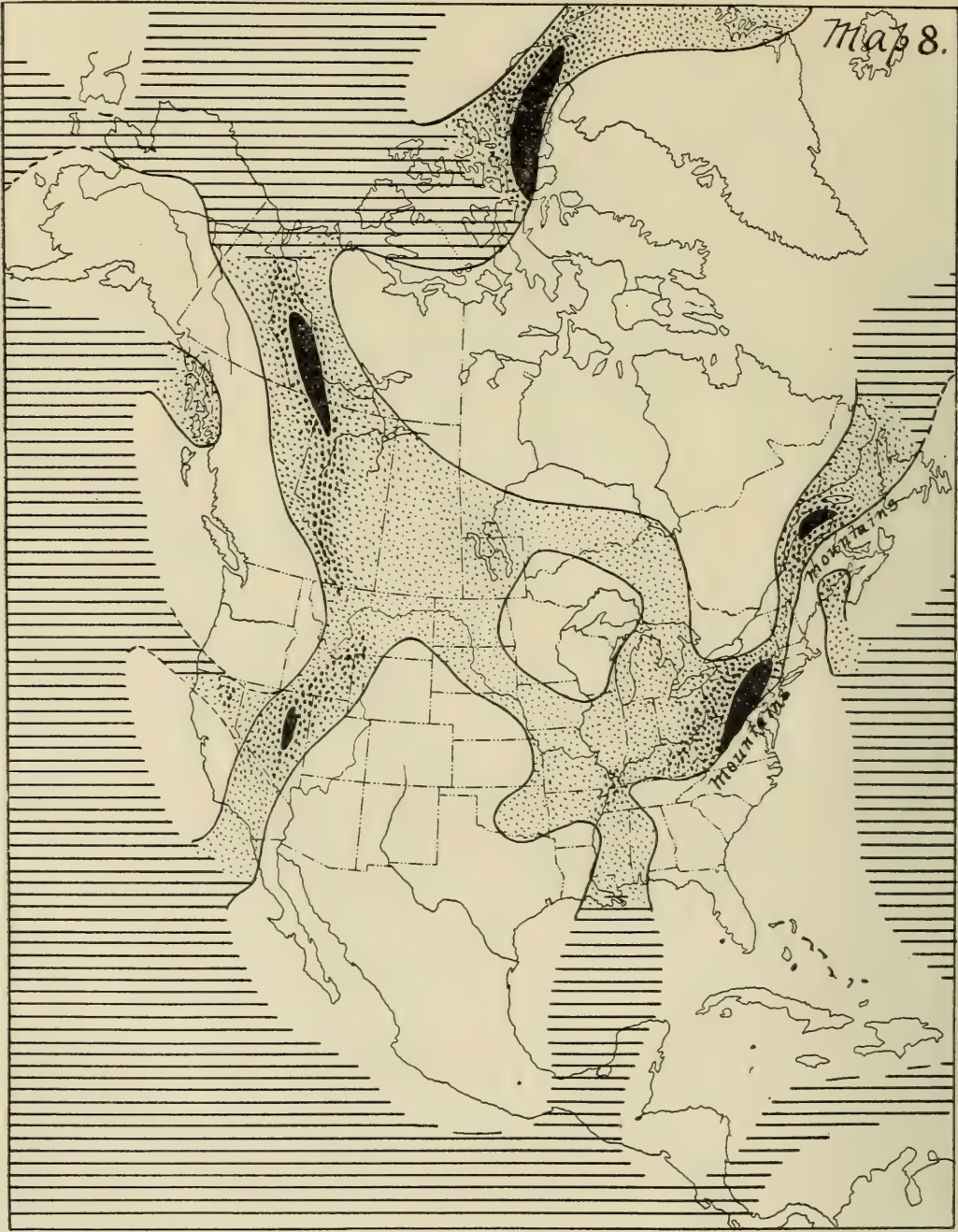


FIGURE 8.—*Geosynclines, Embayments, and their Extensions during Devonian Time*

Intensity of shading indicates areas of greatest subsidence.

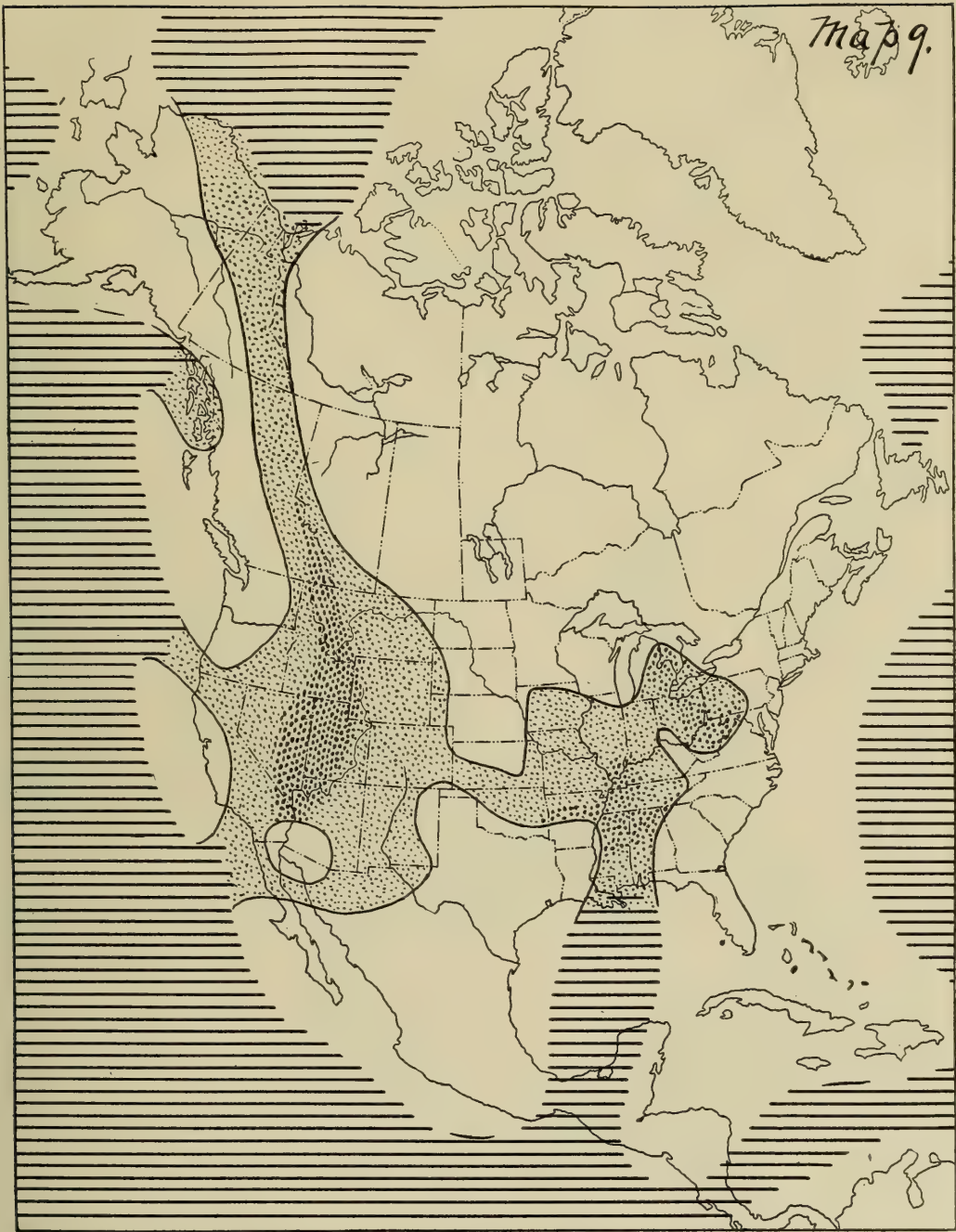


FIGURE 9.—*Cordilleran Geosyncline and Mississippian Sea of early Mississippian Time*

Shading indicates areas of greatest subsidence.

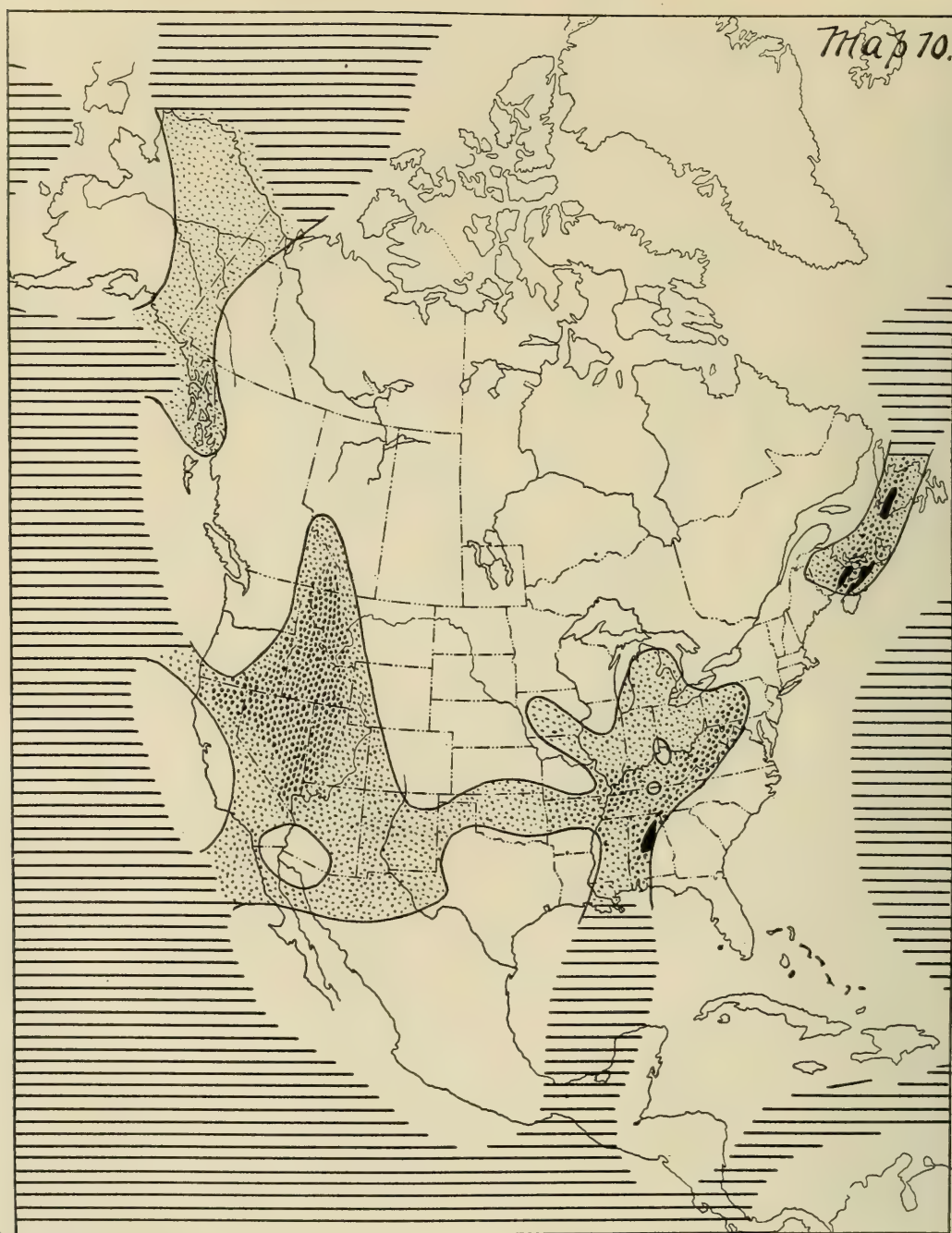


FIGURE 10.—*Seas and Embayments of late Mississippian Time*
Shading indicates areas of greatest subsidence.

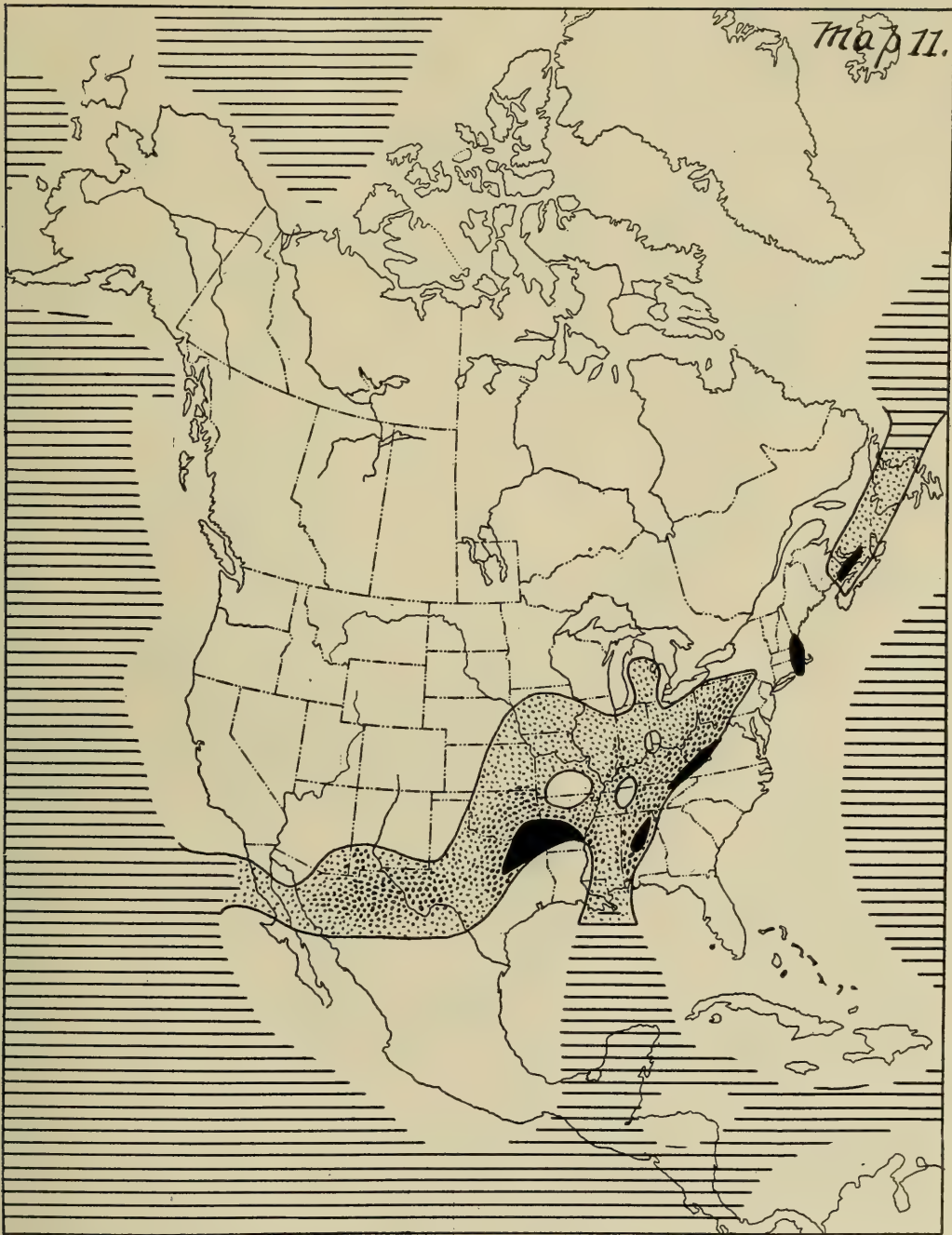


FIGURE 11.—*Seas and Coal Swamps of early Pennsylvanian Time*
Shading indicates areas of greatest subsidence.

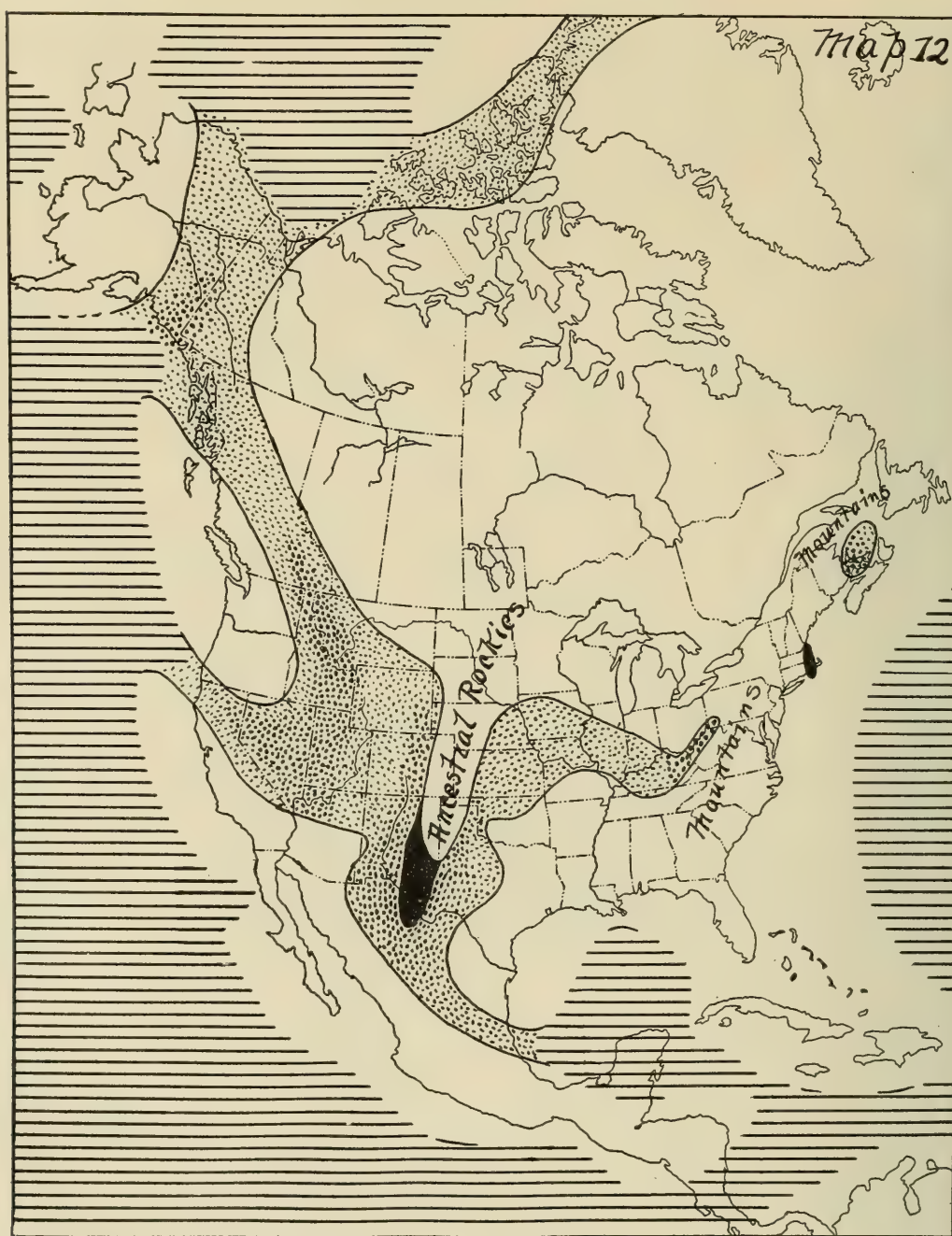


FIGURE 12.—Cordilleran, Mexican, and Franklinian Geosynclines; Mississippian Sea and Coal Swamps of late Pennsylvanian Time

Shading indicates areas of greatest subsidence.

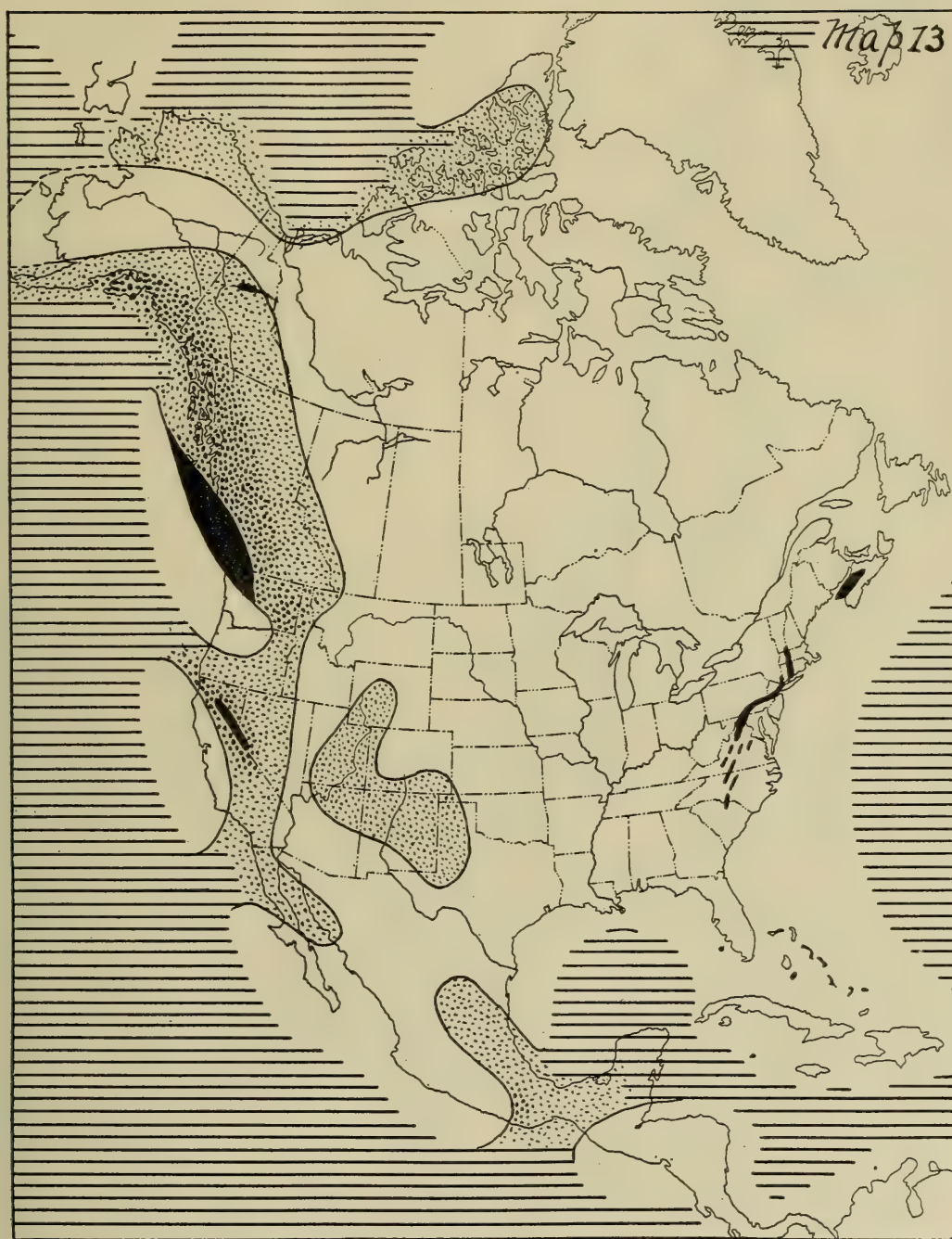


FIGURE 13.—*Pacific Geosyncline, Arctic and Mexican Seas of late Triassic Time*
Areas of fresh-water red deposits in east and southwest. Shading indicates
areas of greatest subsidence.

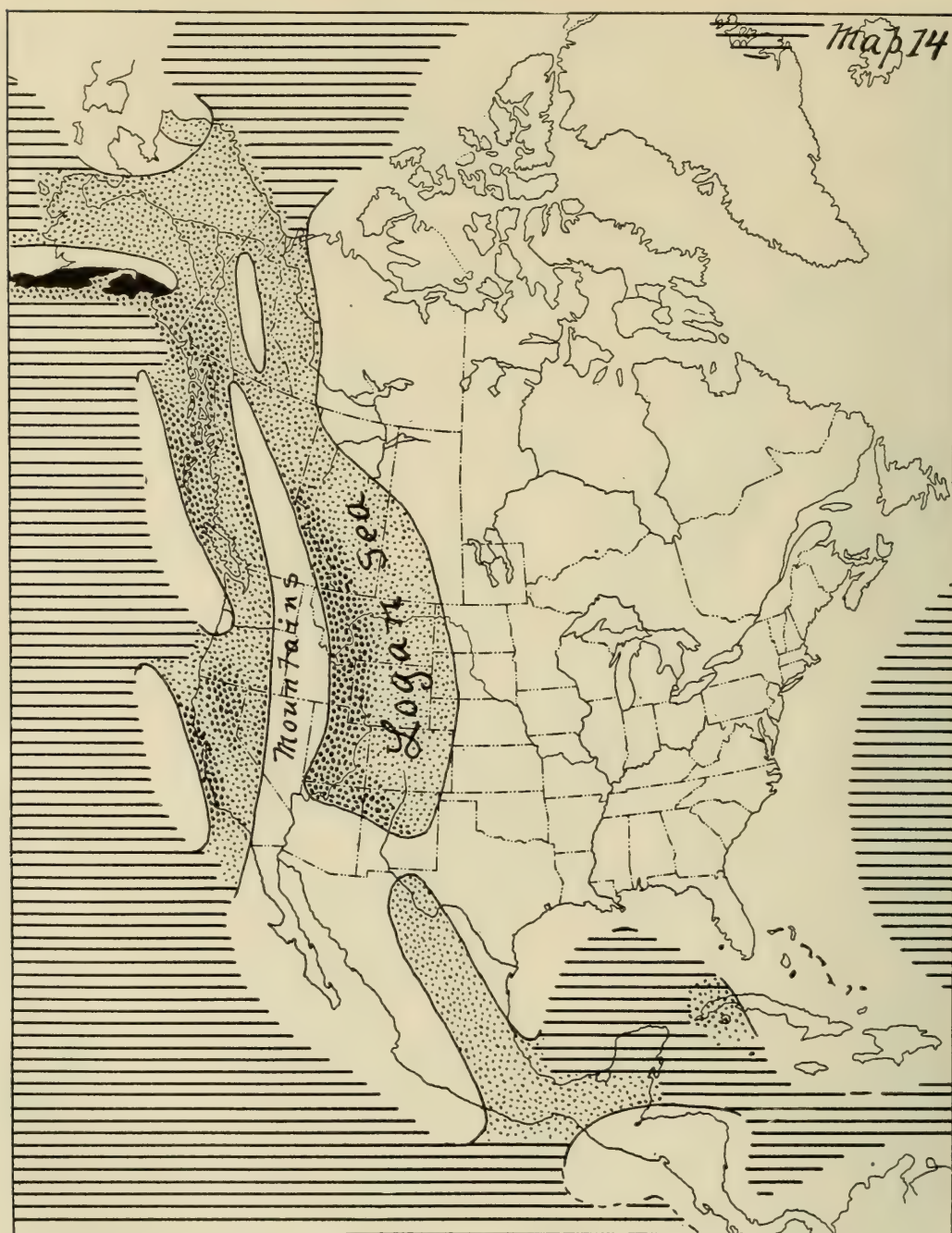


FIGURE 14.—*Pacific and Mexican Geosynclines and Logan Sea of early Upper Jurassic Time*

Shading indicates areas of greatest subsidence.

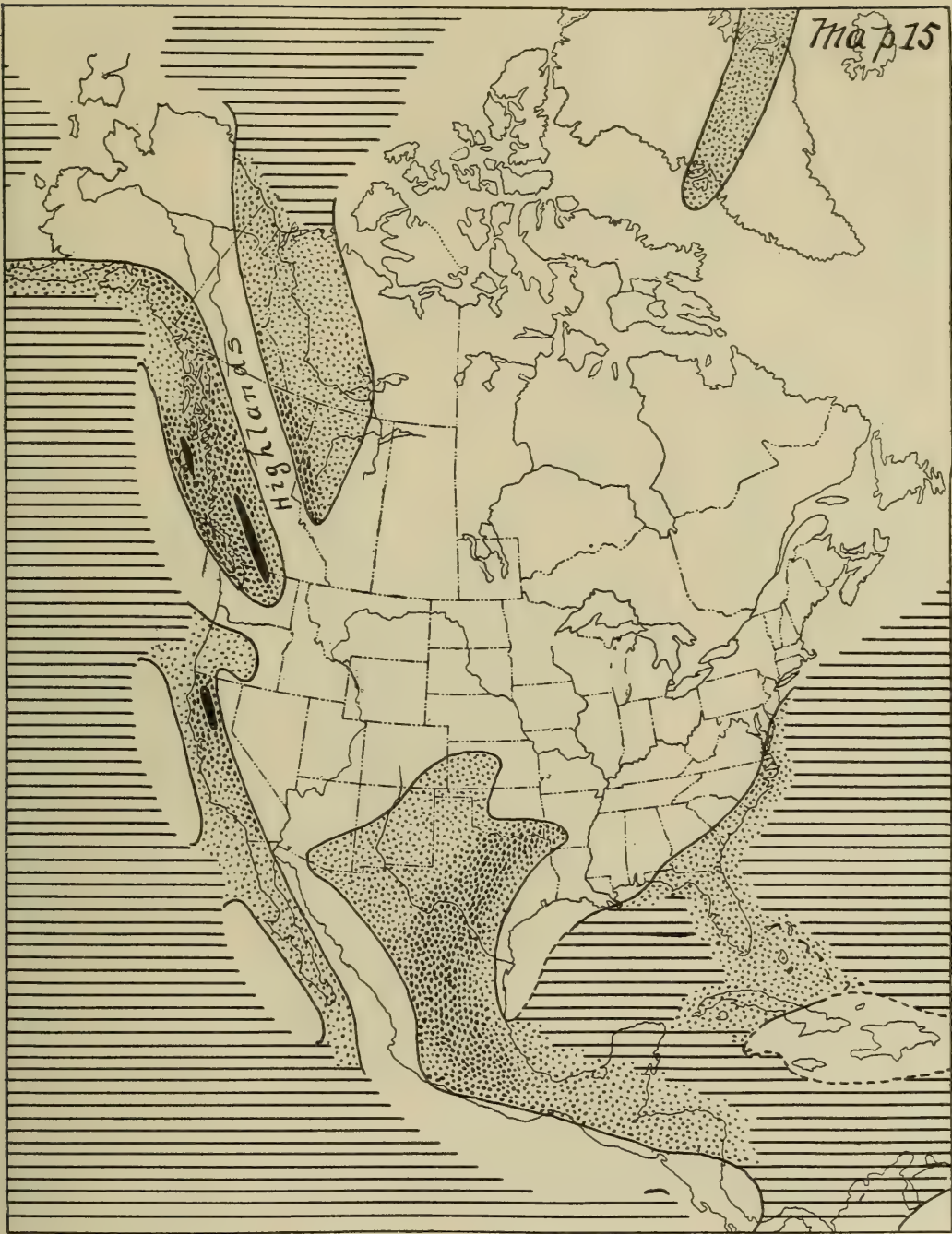


FIGURE 15.—*Californian, British Columbian, and Mexican Geosynclines of Middle Cretaceous (Albian) Time*

Sea over Florida. Shading indicates areas of greatest subsidence.

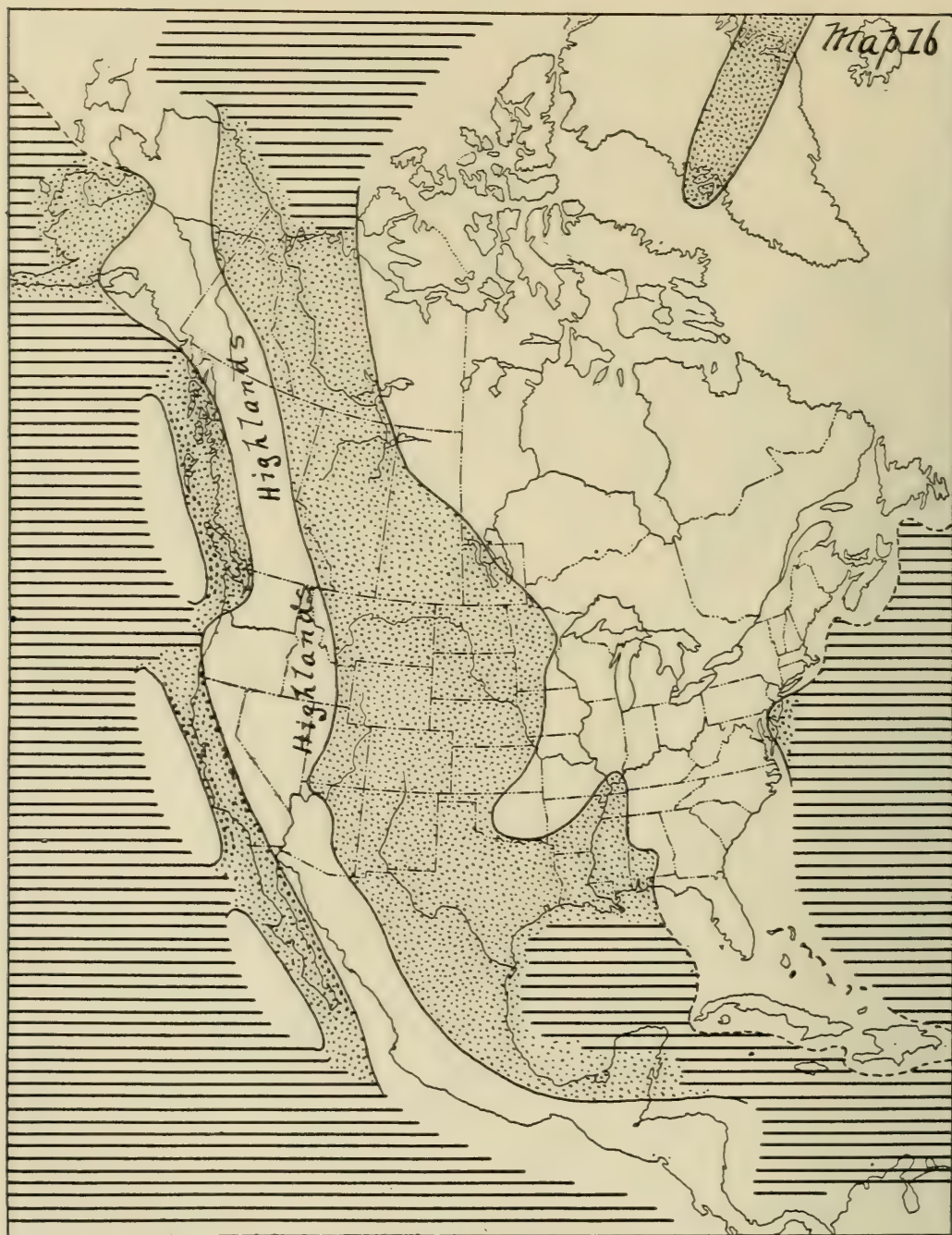


FIGURE 16.—Great Rocky Mountain and narrow Pacific Geosynclines and Gulf of Mexico Overlap of early Upper Cretaceous Time

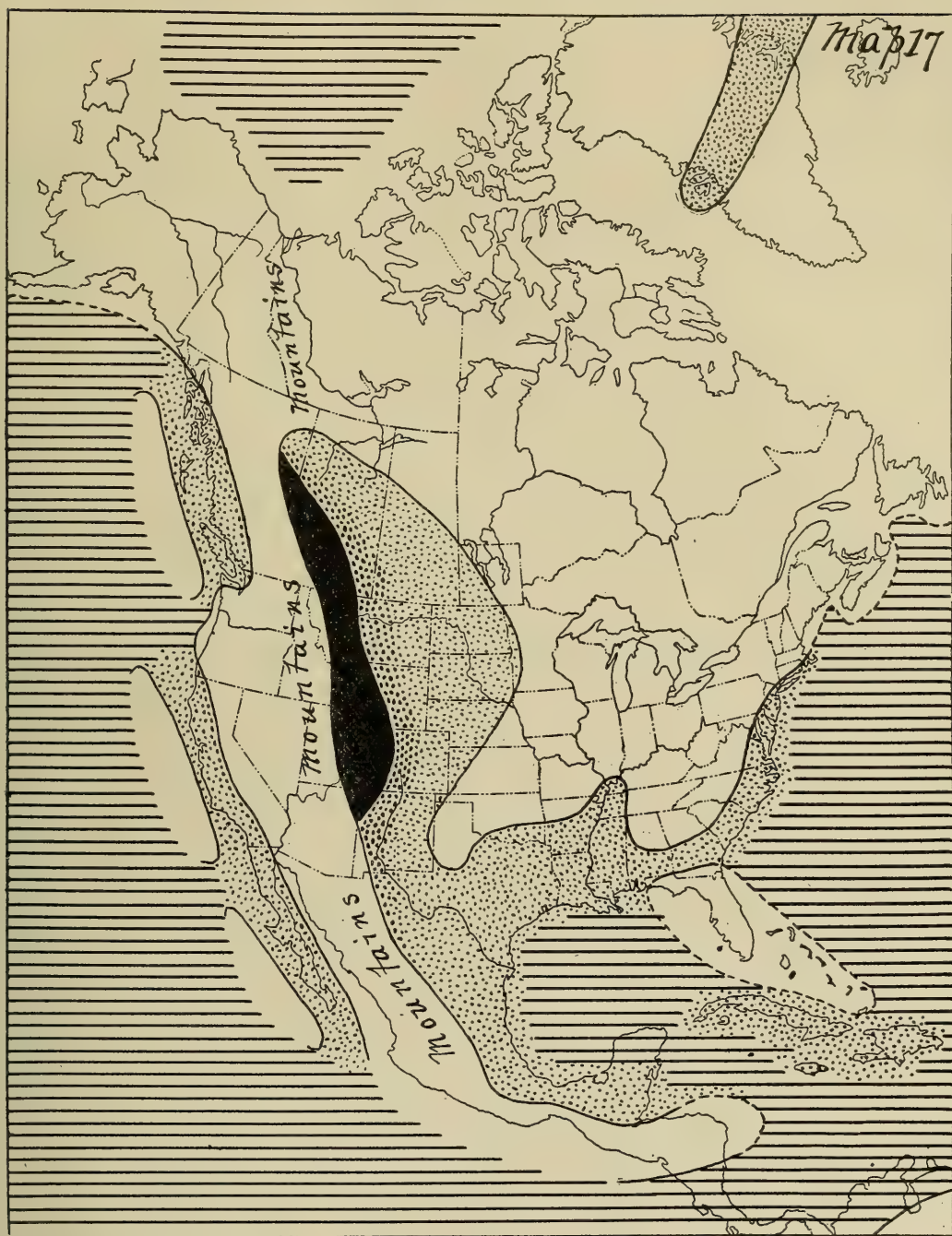


FIGURE 17.—Great Rocky Mountain and narrow Pacific Geosynclines and Gulf of Mexico Overlap of late Upper Cretaceous (Pierre) Time

Shading indicates areas of greatest subsidence.

KOBER'S THEORY OF OROGENY¹

BY CHESTER R. LONGWELL

(Presented before the Society December 28, 1922)

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BRIEF OUTLINE OF KOBER'S THEORY

Professor Kober has attempted to fit all parts of the earth's crust into a broad structural scheme, recognizing major units of two kinds: great plates or shields, continental in size, which behave as essentially rigid masses; and between them sinuous, comparatively narrow zones, which are relatively weak or labile and in which the effects of deformation are concentrated. These *orogenic zones* are marked first by geosynclines, later by great systems of folded mountains. Their positions, as well as the outlines of the plates, have changed somewhat through geologic time. Thus we find within some of the present rigid masses structure lines that mark the sites of mountain zones in the pre-Cambrian or the early Paleozoic. These were belts of weakness which have been healed or welded with the passage of time, while new labile zones have come into existence elsewhere. Therefore details in the structural aspect of the crust have varied, but there has been continued repetition of a general process. In the contraction of the earth the edges of adjacent plates

¹ A review of "Der Bau der Erde," by Leopold Kober. Berlin, 1921.

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This paper is one of a series composing a "Symposium on the structure and history of mountains and the causes of their development."

have pressed against or toward each other, squeezing the relatively plastic orogenetic zones and thus localizing folded mountains.

THEORY AND WORK OF SUSS

In studying the genetic relationships of mountains it is especially important that we recognize the largest units of structure. Exactly what constitutes a complete orogenetic zone and what does it look like in cross-section? Since the time of Suss we have been impressed with the asymmetry of folded mountains. It is a common conception that they are one-sided, the expression of intense rotational forces. Thus we speak of the Appalachians as *overturned* to the west, the Alps to the northwest, the Himalayas to the south, the Andes and northern Rockies to the east. This asymmetric cross-section is nowhere more pronounced than in the famous "decken" structure of the Alps, revealed in the "mountains without roots," which are isolated masses of older rocks standing on a base of more recent formations. It is clear that these anomalous masses are remnants of great overthrust sheets or recumbent folds,² which were pushed northward many miles from their original positions. Deep erosion has exposed a series of these sheets, or even local repetitions of a series, with rocks ranging in age from pre-Cambrian to Tertiary lying in various combinations of superposition. The complex mass has been rolled forward over the foreland, which shows depression under the load.

COMPARISON OF VIEWS OF SUSS AND KOBBER ON THE MEDITERRANEAN MOUNTAIN SYSTEM

Suss pointed out that several mountain systems in the Mediterranean region may be considered as parts of a much larger unit. The trend-lines of the Alps are continued through the Carpathian arc into the Balkans, forming a sinuous but practically unbroken system, with overturning in the same sense throughout. Suss also saw a westward continuation of the Alps through the Apennines, the Atlas, and the Betic Cordillera of southern Spain. Thus he pictured the Alpine system as a great spiral, with its center near Genoa.³ But Kober contends that the Pyrenees and not the Apennines are the proper westward continua-

² Kober evidently favors the older conception of Swiss geologists, that the great "decken" are attenuated recumbent folds rather than overthrust plates. He recognizes a difference in structure, however, between certain "decken," as the Helvetian, apparently developed at a shallow depth, and others, as the Pennine, evidently formed under great load.

³ He recognized the reversal in direction of overturning in passing from the Maritime Alps to the Apennines.

tion of the Alps. Furthermore, following Termier, he considers the Betic Cordillera as entirely distinct from the Atlas and probably connected with the Pyrenees. Proceeding to the east, he projects the Balkan trend-lines through the structures of Crimea and the Caucasus. Thus the Alpides, as defined by Kober, extend from Gibraltar to the Caspian; and in all subdivisions of this great system overturning toward the north is pronounced.⁴

CHARACTERISTICS OF THE MEDITERRANEAN RANGES

The Alpides, considered alone, furnish an excellent example of asymmetry in cross-section, corresponding to the conception of Suess. But Kober says this is only half of the picture. A remarkable counterpart of the Alpine unit may be traced through the Atlas, the Apennines, the Dinaric Alps, the structures of Greece and the Grecian Isles, into the mountains of Taurus and Iran. Again we are dealing with a tortuous but practically continuous line of mountains, with structures overturned

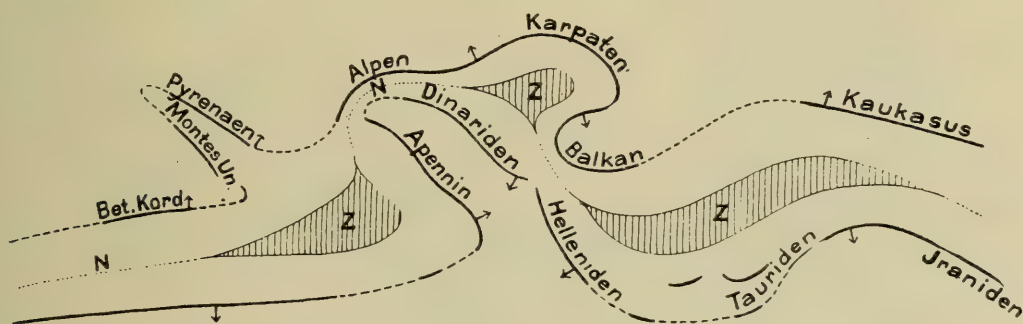


FIGURE 1.—Schema der Gliederung des alpinen Orogen

Kober's figure 26, page 140.

in the same sense throughout; in this case southward, away from Europe and the Alps. It is clear that all of these Mediterranean ranges have a close genetic relationship, for they were born of the old sea Tethys during Cretaceous and Tertiary time. Considered together, they outline a complete orogenetic zone, or *orogen*, with the following characteristics:

The two parallel systems are overturned away from each other, each over its own foreland. Measured from one foreland to the other, the average width of the entire unit is about 1,000 kilometers, although locally it varies considerably from this figure. Typically, as in the Hungarian lowlands and in central Asia Minor, a broad intermontane

⁴ With regard to the Caucasus, Kober is at variance with several other geologists, including Suess, who have reported these mountains as overturned to the south.

space—the *Zwischengebirge*—is relatively little deformed. Elsewhere, as north of the Adriatic or west of the Balkan arc, the border ranges are pressed back to back, with no intervening space. Due to unequal stresses or partly to an original irregular course of the orogen, there are local deep embayments where ranges of the same system face each other. The most pronounced of these irregularities is represented by the Apennines and the Dinaric Alps.

Kober's *orogen*⁵ of the Mediterranean type is represented in section as well as in plan by figure 2. The degree of bilateral symmetry shown in the diagram is, of course, ideal, but with certain modifications we may consider that the section is taken on a northeast-southwest line through the Carpathians, the plains of Hungary, and the Dinaric Alps. Figure 3 represents a section farther west and more nearly in a north-

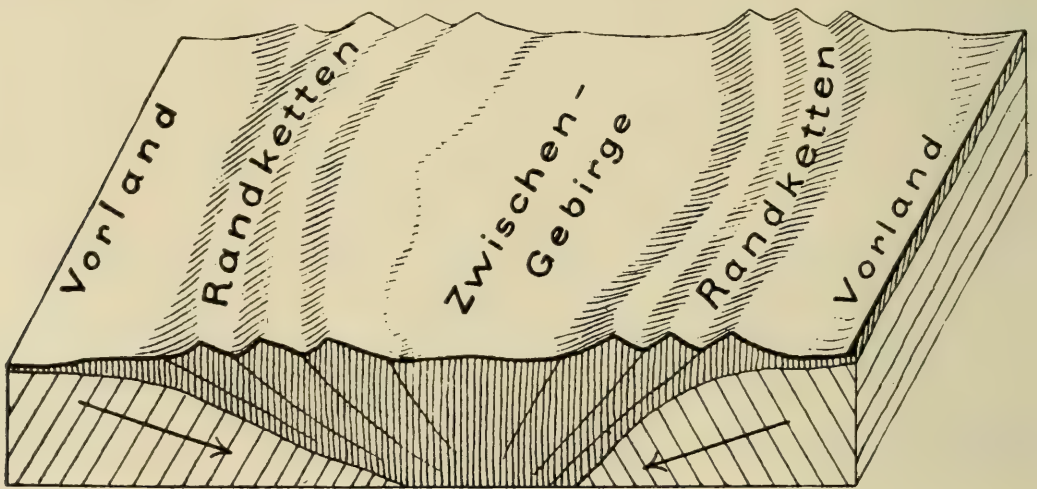


FIGURE 2.—Blockdiagramm eines normalen (erweiterten) Orogen

Kober's figure 30, page 166.

south direction, crossing the East Alps and the Dinaric Alps. This part of the orogen has suffered such extreme deformation, that the rocks of the middle zone (*Zwischengebirge*) are either incorporated in the overfolded borders or depressed into the depths. Folds have been squeezed into recumbent sheets or "decken," which are most pronounced in the East Alps, but also reach southward into the Dinarides. In contrast with the normal section, the separation between the two systems of border ranges is marked by a mere line or cicatrix. The *Narben* (cicatrix) type of structure characterizes the narrow segments of the orogen, which alternate with broader segments characterized by the *Zwischengebirge* type (see figure 1).

⁵ To afford a complete representation of his type *orogen* the diagram should also include foredeeps outside of and paralleling the border ranges.

But the Mediterranean orogen does not stop at the Caspian Sea. The trend-lines of the Caucasus are taken up in the border ranges of Turkestan, deflected northward through the arcs bounding the Pamir plateau, continued eastward through the Kuenlun, and turned to the south on the headwaters of the Hoang-ho. A long belt of chains follows the Mekong, crosses Siam, and finally breaks off at the rias coast of the Gulf of Siam. In this long line of Asiatic chains there appears to be universal overturning in the Alpine sense—that is, generally northward. Typical “decken” structure is reported from several localities. The southern half of the Mediterranean orogen is also traceable through Asia. From the Taurus Mountains we pass into the ranges of Kurdistan, western Persia, and Oman, to the Arabian Sea. In Baluchistan there is a northward curve to join the great Himalayan arc, and in upper Burma the trend-lines are again southward, passing into Sunda arc, which swings eastward to Timor. In this long system of ranges there is consistent overturning toward the south, over Arabia, India, and the Australian platform. In this entire Eurasian mountain belt, extending from Gibraltar to New Guinea, thousands of miles in length and hundreds in width, there is a remarkable correspondence in kind and age of sedimentary rocks, in kind and age of structure. Evidently we are dealing with a great structural unit, an orogenetic zone which has been crushed between rigid

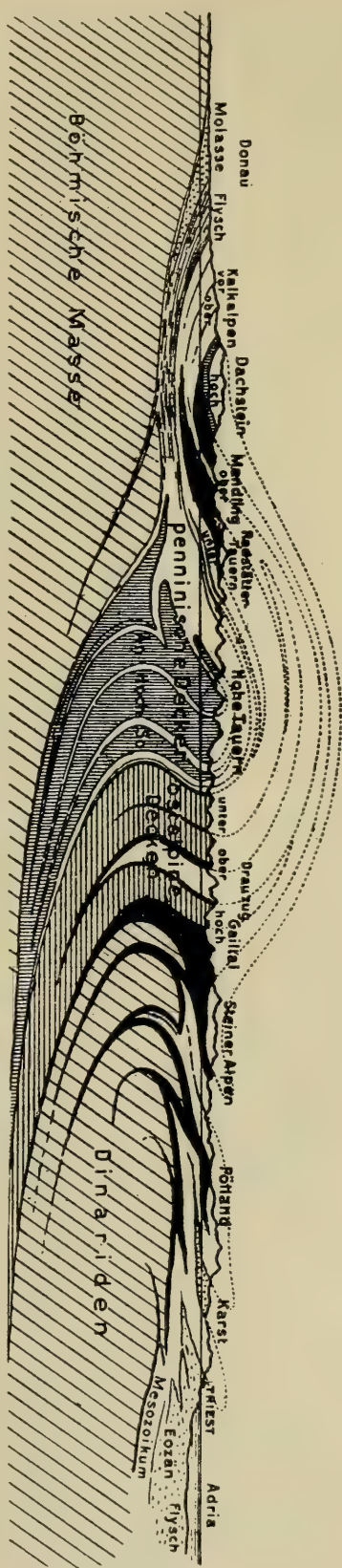


FIGURE 3.—Schema des Deckenbaues der Ostalpen und Dinariden
Kober's figure 23, page 126.

plates of the crust. The northern foreland is Eurasia, the southern a combination of Africa, Arabia, India, and Australia. Intensity of overturning varies from place to place, as do the width of the orogen as a whole and the distance between border ranges. The greatest of the intermontane masses forms the high plateau of Tibet.

COMPARISON OF THE MEDITERRANEAN OROGEN WITH OTHER MOUNTAIN SYSTEMS

We may say, then, that the Mediterranean orogen exhibits bilateral symmetry in section, and its ranges are grouped systematically in ground plan. It will be well to examine other mountain systems for evidence of similar relationships. Paleozoic mountains have been eroded, fragmented, buried under later sediments, and therefore in many cases the complete plan of their architecture is not evident. Thus in the Altai

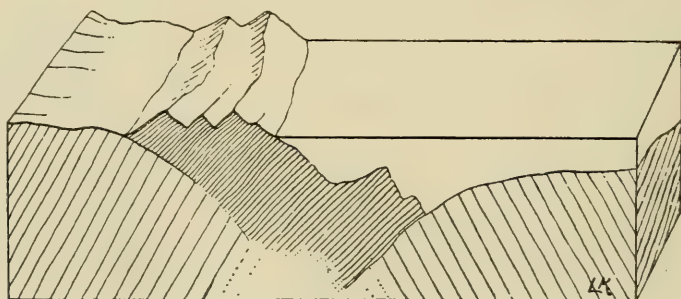


FIGURE 4.—*Blockdiagramm eines mit einem Vorlande einseitig versenkten Orogen*

Kober's figure 33, page 167.

Mountains we see overturning to the north, over the old Siberian table, but farther to the south the structures are obscured, due to later deformation. In the Urals a partly resurrected Paleozoic system, folds, and "decken" reaching both east and west are exposed, conforming to Kober's theory. A still better illustration is found in the post-Silurian Caledonian Mountains, represented on one side by the great Scandinavian overthrust to the east and on the other by the Scottish overthrusts to the west. The middle portion of the orogen has sunk beneath the sea.

We turn now to the Western Hemisphere. Kober has read of structures overturned westward along the Pacific coast of North America, and of the Rocky Mountain overthrusts to the east. He seeks to join these widely separated features to form a single orogenetic zone. Those who are familiar with the mountains of western North America will not consider this interpretation seriously. It appears, however, that a suggestion of Kober's plan exists on a more limited scale in the Jurassic structures of California and Nevada, which exhibit overturning to the

west in the Sierra Nevada Mountains and thrusting to the east in southern Nevada.⁶ In the Appalachians evidence has seemed to indicate overturning toward the west only; but Kober reminds us that the old land Appalachia has been completely submerged, and he believes the eastern half of the Paleozoic orogen has foundered with it. Support of this theory would be furnished by finding along the Atlantic coast remnants of structures with overturning to the east:

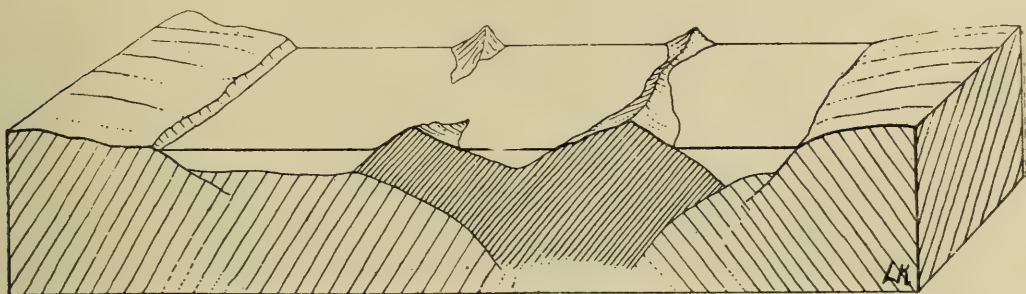


FIGURE 5.—*Blockdiagramm eines normalen versenkten Orogen, dessen Vorland z. T. stehen geblieben ist*

Kober's figure 31, page 166.

He uses similar argument in the case of the Andes, where dominantly eastward overfolding and thrusting have been reported. An old land-mass to the west has certainly disappeared, and he believes the western limb of a great orogen went down with it, leaving only the eastern border ranges exposed. This explanation calls for selective faulting on a rather large scale, for it demands quite accurate cleaving of an orogenetic

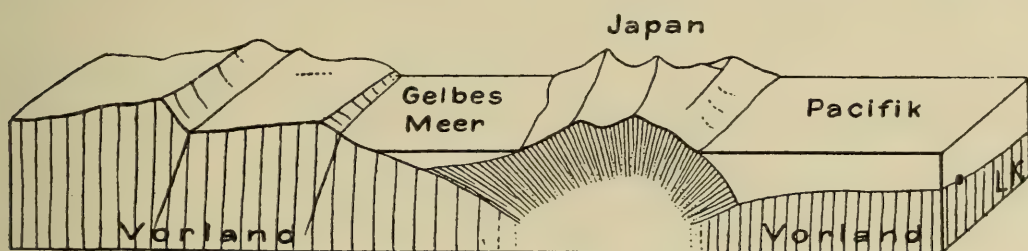


FIGURE 6.—*Blockdiagramm des japanischen Orogen*

Kober's figure 34, page 168.

zone along its median line throughout the length of a continent. But Kober thinks we should expect various modifications of the typical orogen. One foreland may be submerged and one entire system of

⁶ Evidently Kober is not aware of this relationship, and it appears that he does not consider the great discrepancy in age between the folding in the Sierra Nevada and the Rocky Mountain thrusting. Other erroneous conceptions are evident in his discussion of North American geology.

border ranges with it (figure 4). Parts of both forelands may break down, carrying the entire orogenetic zone, perhaps leaving the tops of border ranges projecting above sealevel as chains of islands (figure 5). The island chains east of Asia may represent a combination of these two modifications (figure 6). The eastern foreland is covered by the Pacific; a typical foredeep borders Japan; the Yellow Sea is a shallow, partly filled foredeep, and the western foreland is partly broken

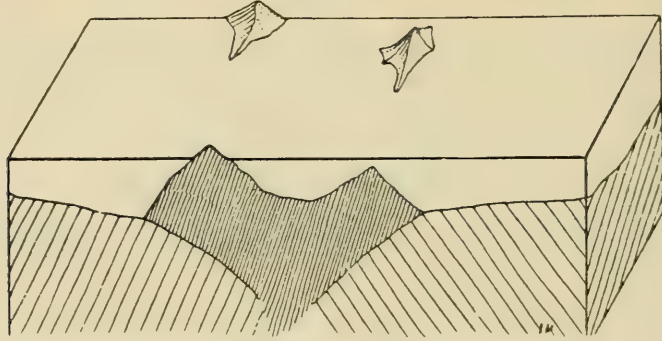


FIGURE 7.—*Blockdiagramm eines samt dem Vorlande versenkten Orogen*

Kober's figure 32, page 167.

down. Again, both forelands and most of the orogen may be submerged (figure 7). Perhaps this type is represented by the island chains of New Caledonia and the New Hebrides. The suboceanic ridge extending north and south in the mid-Atlantic may be an orogen of which no portion rises above sealevel.

MOUNTAIN GROWTH

What forces are involved in the building of a two-sided mountain system and how do they operate? The motive power for folding and thrusting is probably furnished by contraction of the earth. Compression due to contraction is, no doubt, continuous, but in any orogenetic zone periods of deformation alternate with periods of quiet, during which stresses accumulate. But the requirements of gravity must be satisfied in the crust. Tangential movements, with localization of deformation, tend to build up an excess of material in an orogenetic zone, which then subsides under the overload. If subsidence is sufficient, the zone becomes an area of sedimentation, and is further depressed under the weight of detritus. This marks a geosynclinal or negative stage. As the zone sinks, the geotherms are depressed; then slowly rise. The increase in temperature and resulting chemical reactions probably do not affect the crust of sediments so much as the deeper portion of the lithosphere beneath the geosynclinal area. Energy arising from the reactions

and from thermal expansion probably serves chiefly to disturb equilibrium, setting in motion the larger forces due to contraction. The materials of the orogen become more plastic with heat—perhaps portions actually liquefy—and the deeper part of the zone becomes honeycombed with magma. Under lateral pressure from the rigid plates the plastic mass tends to rise and the overlying sediments are folded. The entire orogenetic zone acts as a passive mass between the jaws of a vice, and as great folds rise on either side of the geosyncline they are underridden by the rigid plates, and so turned back over the forelands. Other folds form inside of and parallel to the first, and if compression is intense and long continued the entire body of sediments will be crumpled. In a wide geosyncline the forces will ordinarily be spent in folding up the border ranges, and the sediments of the middle zone will escape intense crumpling. This interior (*Zwischengebirge*) zone occupies the deepest and most plastic portion of the orogen. There isostatic compensation will be almost completely maintained, even during periods of active mountain growth, and very little actual elevation may occur. The rigid plates in part support the overfolded border ranges, and thus in some degree superior elevation may represent an overload. Yielding to the overburden may take the form of sagging or major faulting, either at some stage of mountain growth or at a later date, and considerable portions of a foreland may be carried down in the failure.

Kober's ideas of mountain growth as illustrated in the Alps are best expressed in his own words, as follows:⁷

"The Alps arise on the site of the Paleozoic mountains. During the Mesozoic these were in large part leveled down and sank more and more into the geosyncline. But not all parts alike. The pressure from contraction allows some parts to sink deeper than others, and thus there are formed more or less parallel sea basins on the floor of the geosyncline lying in the area of contraction. Major synclines and geanticlines originate, alternating from north to south. The great anticlines become embryonic *decken*; these change in the course of mountain-making through the Mesozoic to *trunk decken*, from which secondary *decken* (*Teildecken*) later branch off. The *decken* move slowly and steadily on the sea-floor against the foreland, gradually rise above sealevel, develop into islands, rows of islands, island chains, and finally into connected mountain features (Argand and Staub). It is a 'mechanics of great folding,' as we may say with Abendanon, a moving of *ground folds* (Penck), which increases in magnitude, develops into geanticlines, between which great synclines lie deeply depressed. The geanticlines are finally overturned; their own weight drags them down into the synclines; these are concealed (overthrust). A period of quiet follows. Then the next geanticline is thrust forward. The process is repeated. Then the previously formed geanticline revives, is thrust over the one lying before it; both move together

⁷ *Der Bau der Erde*, pp. 92-93.

farther on the foreland and cover the area in front with their *decken* wall, or thrust it forward, squeeze it, overturn it. Phases of quiet follow intensified mountain-making. This is all plainly expressed in the sediments. The breccias always originate during the phase of unrest; they define the manner of mountain-making as to time and place, and are therefore valuable guide horizons in unraveling the genesis of a *decken* mountain system. The conditions of sedimentation become increasingly complicated with the evolution of *decken*. Out of the rubbish of the *decken*, strata may form on the sea-floor, which in turn are made into *decken*.

"The *decken* movement is from the inner parts of the geosyncline outward, and it advances continually against the rigid plates of the foreland. This also may be included more or less in the powerful movement and drawn into the whirlpool of the orogenic field of force. The more the geosyncline is compressed, the more will it rise as mountains and become *terra firma*. There follows the phase of arching up the *decken* ranges into lofty mountain chains. Steinmann has designated this phase as *positive* mountain-making. According to Heim, this phase is followed by a further one, which is characterized by the sinking of the mountain chain, immersed like an iceberg in

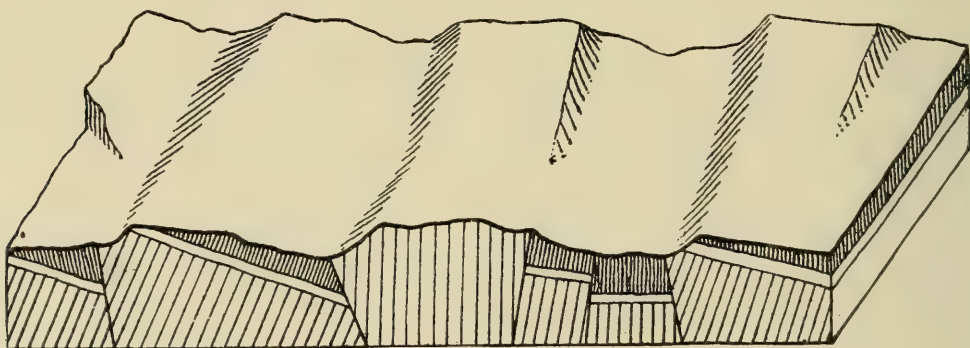


FIGURE 8.—*Schema des Graben-Horsttypus*

Kober's figure 1, page 51.

the sea, as a consequence of its enormous size and weight. This is a sort of closing phase in the making of a young *decken* mountain system. Perhaps this may be designated as the *negative* phase. The positive phase is characterized by the division of the mountain system into blocks (Schollen). The mountain chains rising out of the sea remain for a long time near sealevel, and undergo there widespread planation, as is seen in the East Alps (pre-Miocene, pre-glacial surfaces). The Alps at that time had not the character of a high mountain system. They were rather a hill country or mountains of moderate height. Only positive mountain-making forced the Alps to great heights. It is said that these movements are epeirogenic. As a matter of fact, they are expressed chiefly in fractures and flexures, in arching of the old land surface. But these epeirogenic movements, as was stated previously, are disguised orogenic movements, involving fractures which may later become overthrusts. In any case they are not movements of an entirely different sort, but merely continuations, through a short time interval, of the orogenic or *decken* movements."

Throughout his discussion of diastrophism Kober emphasizes the part played by compressive forces, which probably have their origin in continued contraction of the earth body. He even conceives that horsts and graben in a region of block-faulting are bounded typically by reverse rather than normal faults (figure 8). The Rhine Valley and the African Rifts are explained by failure at the crests of broad anticlinal arches, and so are essentially features due to compression. Unlike many exponents of the contraction theory, however, he is alive to the import-

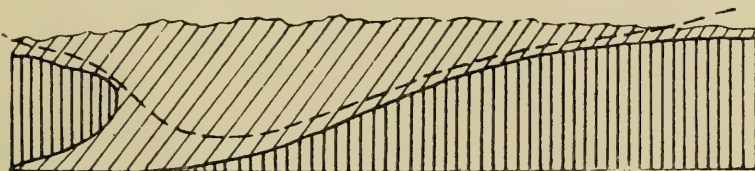


FIGURE 9.—*Schema eines Gebirges mit Massendefekt*

(Dotted line represents theoretical surface of normal gravity.)

Kober's figure 21, page 97.

ance of isostatic control. Relief features are largely compensated, mountain ranges standing high by virtue of deficiency in density (figure 9). When an orogenetic zone is undergoing folding, more material is forced into the depths than above the general surface. There is continual conflict between tangential and vertical forces. If excessive matter is crowded into a zone, sinking will eventually ensue, although a certain degree of overload may be borne for a time. Thus uplift and subsidence may occur alternately in essentially the same zone through several geologic periods.

THE ASIATIC ARCS¹

BY WILLIAM HERBERT HOBBS

(Read before the Society December 28, 1923)

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ESCHER'S DEFINITION OF BILATERAL SYMMETRY

All earlier studies of folded mountain ranges ignored the relationship between plan and cross-section or profile. Largely in consequence of this neglect, the forces to which they have been supposed to owe their structure have been assumed to possess a bilateral symmetry. For the classical area of the Alps, the folded region which has been studied for the longest time and in the greatest detail, this idea of bilateral symmetry was expressed in the words of Escher and his pupil Heim as *zweiseitigen Druck*.

ASSYMMETRICAL ARRANGEMENT OF RANGES

It was Eduard Suess who as early as 1875, in his *Die Entstehung der Alpen*, by focusing attention on the plan, rather than the profile, of mountain ranges, showed that an asymmetrical arrangement of the ranges within definite arcs called for an asymmetrical disposition of the forces which had produced them. Very shortly thereafter James Dana, in studying the other classical area, the Appalachians, adopted a theory of their formation which required the force producing them to come mainly from one side—that of the ocean. In 1884, the year in which his close friend, Marcel Bertrand, made public his conception of the

¹ Manuscript received by the Secretary of the Society March 24, 1923.

This paper is one of a series composing a "Symposium on the structure and history of mountains and the causes of their development."

blanketing slide or *nappe*, there appeared the first volume of Suess's *Das Antlitz der Erde*, in which the pregnant idea of the unsymmetrical mountain arc was shown to have an almost universal application. Overcoming the most stubborn opposition, the idea of one-sided (*einseitigen*) as opposed to two-sided pressure (*zweiseitigen Druck*) at length made converts, even of its enemies, notably Lugeon and Heim, who are today the foremost expositors of the doctrine of one-sided compression.

VIEWS OF KOBER

Ignoring all the evidence derived from the plan of the arcs, it has remained, strangely enough, for a Viennese student of mountains, Leopold Kober, to revert to the now long-abandoned idea of symmetrical bilateral disposition of the compressive mountain-building forces. The Alps are by Kober connected up to the Atlas Mountains in Africa as though they comprised a single folded area, and the well-known profiles have been so distorted as to make a supposed folded zone, about one thousand miles across, extend downward into the earth's shell a distance of some 300 miles, so that horizontal compression might appear to get enough "hold" to compress the lens—but what Kober draws as a wedge—of sediments, on which the forces are none the less made to act at a very acute angle. Such a symmetrical distribution of forces he then by an even greater distortion of the known profiles has made to apply to most other folded mountain ranges.

There are four well-known regions, and four only, where *by extending from one range to another across broad intervening non-mountainous areas*, as Kober has done, such a bilateral symmetry can be made out. Three of these are on the site of the former Sea of Tethys and its extensions—what Emerson has called the zone of the intercontinental sea² and the author the twin zone of the earth.³ The fourth example is that of the South Shetland Islands, lying between the southern apex of South America and the Antarctic Continent.

It may fairly be claimed that among students of mountain formation the idea of "one-sided" as opposed to "two-sided" compression has received general acceptance, though for correct terminology we should say that what the idea involves is really an excess of lateral compressive stress from one side of the folding range, which results in actual movement of a portion of the rock layers from the side of the greater stress toward that of the lesser.

² B. K. Emerson: The tetrahedral earth and the zone of the intercontinental seas (presidential address). Bull. Geol. Soc. Am., vol. 11, 1900, pp. 61-96, pls. 9-14, figs. 1-7.

³ W. H. Hobbs: Earth evolution and its facial expression. Macmillan, 1922, p. 92.

SUESS' THEORY AS TO MOUNTAIN ARCS

To account for the mountain arcs, Suess claimed that the system of stresses which produces them has an unbalanced thrust from the rear, and this view has since been quite generally accepted. In his *Erinnerungen*, which were published posthumously in 1916, he reveals more clearly than anywhere else that he came to adopt this conception because of the position of the Bohemian "obstruction" of granite and gneiss in Europe opposite the vertex of the Alpine and Carpathian arcs, which arcs appeared to him, therefore, to have moved northward at either side where not so "obstructed." Probably also unconsciously the fact that viscous substances flow outward to produce convex borders played some part in fixing this conception in his mind.

AUTHOR'S VIEWS AND CONCLUSIONS

Mountain arcs are, however, very numerous, and such obstructions along their front as the Bohemian mass are altogether exceptional, the only other noteworthy example being that of peninsular India. I have therefore examined the question of the mechanics of arcuate mountain formation and reached the conclusion that the excess of tangential compressive stress which is responsible for the evolution of the folded arc has come from the front and below instead of from the rear and above.⁴

The Asiatic arcs taken together comprise by far the most perfect illustration of the folding process that our planet affords. They represent a more or less concentric series of compounded arcs which surround the ancient continent of Angara, with each series made up of a number of arcs linked together. Their study has shown that they have been formed in successive periods, and this not alone on the basis of the strata involved in the folding process, but quite as certainly by the stage of the erosional process which each illustrates.

It is a generally accepted fact that the effect of close folding is to give to the strata affected additional rigidity, and this should have the effect of causing the area in process of folding to migrate beyond the already formed folds, though such stresses appear to be limited as regards the distance to which they are carried forward within the folded layers. The well-known experiments of Willis on the folding of strata confirm this view.

The plan of the Asiatic arcs is so extended that it is possible to apply a test to determine what has been the sequence of formation of the

⁴ Earth features and their meaning, 1912, pp. 437. Mechanics of formation of arcuate mountains. Jour. Geol., vol. 22, 1914, pp. 71-90, 166-188, 193-208, figs. 39. Earth evolution and its facial expression. Macmillan, 1921, chapter x.

several festoons of arcs—their order of succession in time—and so to determine whether the deforming unbalanced stresses have come from the front or the rear. These festoons of arcs bear such close relations to each other as parts within a system that what has been true of one has in a general way been true of the others, as regards the method of their formation. In other words, we are here dealing with the large problem of the deformation of the continent of Asia under the influence of a system of crustal stresses which have acted over a long period of time and have involved vast areas.

As a part of this system of arcs, the festoons of islands which parallel the coast are from the relation of their design to that of the ranges upon the continent to be included in the system. The striking difference between the several arcuate series within the system, both as to the ages of the strata involved, the topographic development, the erosional stage, etcetera, indicates that they have been formed at different times; and since these differences are in a noteworthy degree graded from the interior of the continent toward its margins, they may be assumed to have been formed in succession. The question is whether the interior or the exterior arcuate series is the initial one in the succession, and this will obviously depend on whether the surface shell of the lithosphere has migrated after the fashion of a glacier in the direction of the surrounding seas or whether a thrust coming from the seas and directed against the borders of the continent has in successive stages raised a ruffle along its margin.

The maps and accompanying sections of figure 1 represent an attempt to set forth these contrasted views with their necessary corollaries, the first (map and section A) setting forth the generally accepted view of Suess that the thrust has come from the back of the arc, the second (map and section B) the view of the author that this thrust has come from the front. Mountain ranges in process of erection are well known to be zones of seismicity and to be further accompanied by active volcanoes, and these elements have been introduced into the maps. Moreover, inasmuch as erosion is always in sensitive adjustment to uplift, the degree of denudation which should under each of the views be expected in each series of arcs is displayed in the sections.

Especially to be noted is the condition of marked compression from opposite sides of the arcs within the southeastern extension of the continent in the direction of Australia. In case the outer skin of the continent of Asia is conceived to have migrated centrifugally, as implied by Suess, the position of the ancient coign of Australia should have the effect of broadening the arcs in proportion as they approach this "obstruction."

On the other hand, if the system of thrusts has gone out from the oceanic areas and been directed against the margins of the continent, the coign of Australia must be regarded as a protective shield which has warded off any thrust from the southeast, while the thrusts on the Malayan region from its opposite sides (northeast and southwest) should have resulted in a much greater compression of these arcs than is elsewhere to be found. In a broad way, the map and section B represent the facts so far as they are known.

An obvious cause of the landward thrust from the sea, which is here invoked as the cause of formation of mountain arcs, is the still continuing subsidence of vast areas in the Pacific and Indian oceans, to which the formation of the groups of atolls bear testimony.

The marked zone of seismicity and the line of active volcanic vents which alike follow the course of the festoons of islands off the coast of the Asiatic continent seem clearly to reveal them as the very youngest of the Asiatic arcs and those which are in the process of erection today on the floor of the sea with their summits just emerging from the waves. Believing that, in geology as in zoology, it is in the embryo that the life history is often most clearly revealed, the writer during the summer of 1921 carried out a reconnaissance of these youngest arcs, in connection with which he visited islands of the Bonin, Sulphur, Marianne, Caroline, Pelew, and other groups with a view especially to find evidence of continuing mountain growth and to check this by observing the stage of the erosional process, as well as the nature and comparison of the reef structures on the opposite sides of the arc. These latter are of particular value in revealing the structure of an anticline, and in practically all earlier stages of arc formation proceeding within the tropical seas, wherever conditions suitable for reef-making have existed, elevated reef-caps appear as terraces on the convex outer side of the arc and barrier reefs indicating subsidence on the opposite or concave side.

In a later stage of arc formation alternating vertical movements of great amplitude develop along the medial portion of the convex side of the arc, so that here also barrier reefs develop. These central zones off the front of an arc in a late stage of its development are regions of special unrest of the sea-floor and in this respect surpass anything which is elsewhere known. Here are the special loci of seaquakes which have been such a menace to the navigator, while at the same time the arcs are the vigias or sign-board warning of the danger.

The erection of an evolving anticline does not appear to take place at a uniform rate throughout, but there first arise a series of domes in arcuate arrangement which only later unite to form a uniform crestline

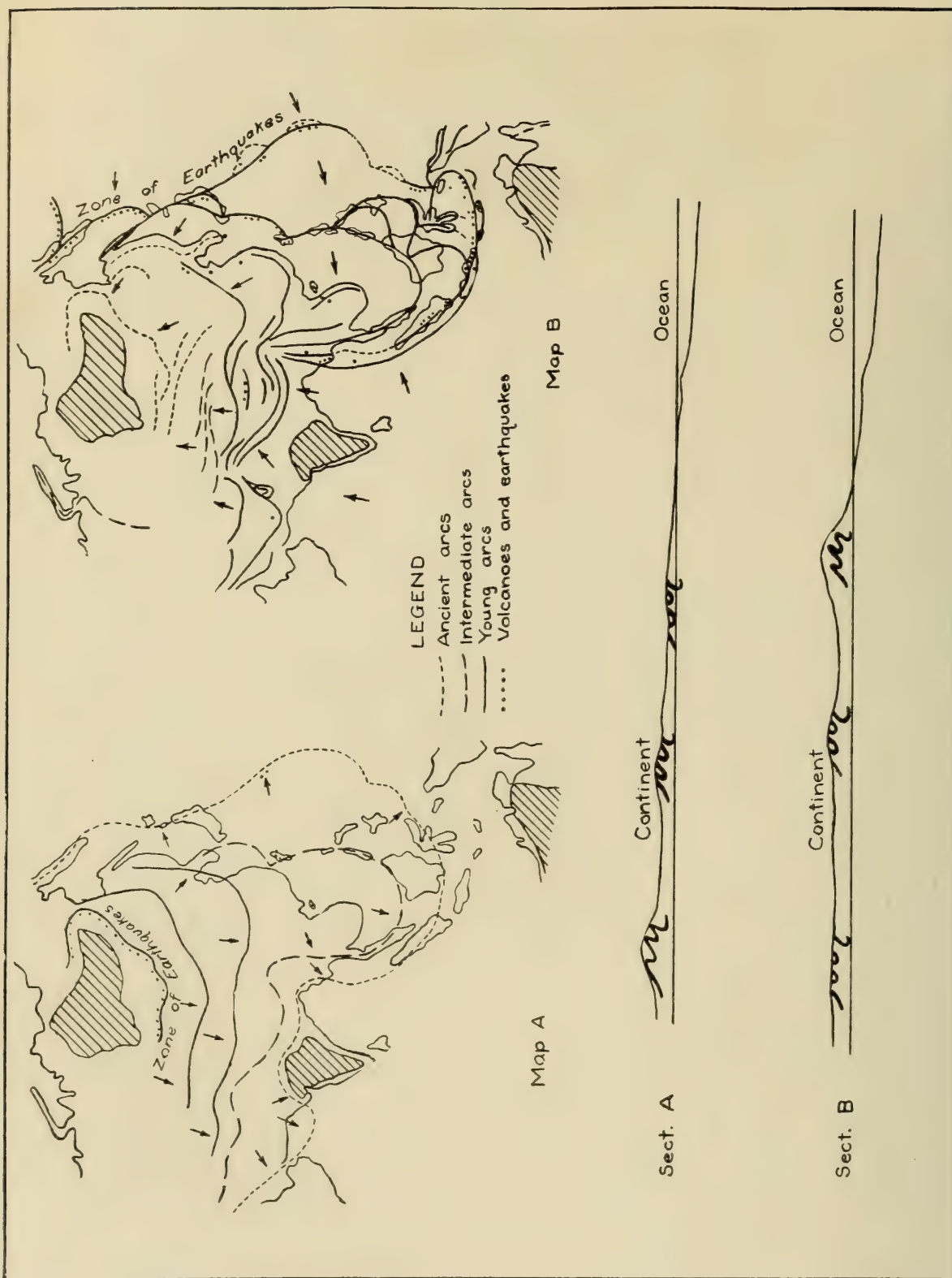


FIGURE 1.—Contrasted Maps and Sections of the Asiatic Continent

These drawings represent the views of Suess (A) and the author's views (B) concerning the order of succession of the mountain arcs.

for the arc. In this respect the writer's view differs materially from that of Brouwer, who sees in the straits which separate the islands of an arc the evidence of late tensional movements which he supposes to result from a forward migration of the arc by a push from behind.⁵ The evidence that the arcs of today rise first at special points appears to be confirmed by those older arcs which skirt the eastern flanks of the Rocky Mountains.⁶

No sooner does an anticline rise to form an arc than an elongated and roughly parallel trench—*fore-trench*—begins to develop along its front, and the crucial test to determine whether the arcuate arrangement of a group of islands may not be fortuitous, and hence without tectonic significance, is exactly the presence or absence of such a fore-trench. Hence the great importance of carrying out an elaborate series of soundings in the neighborhood of all growing mountain ranges of the oceanic areas. There is in the development of the fore-trench opposite a rising arc an apparent indication that the void which should tend to develop beneath a rising arch in the strata is met by a lateral migration of subsurface material from in front of the rising anticline—an isostatic adjustment which follows as a consequence of mountain erection, but is in no sense an initiator of it. The anticline and syncline from this stage appear to develop together. In those later stages where arcs have taken on a sharp curvature the trench appears at the back instead of the front of the arc, notably in the examples of the Moluccan and Windward arcs.

Within coral seas where atolls are to be found, the earliest evidence of arc formation may be the elevation of such atolls, and these may be detected today in very many cases by their deposits of phosphate, such islands being far more numerous than is generally supposed.⁷

In the study of the young island arcs, examination of each island is essential in order to determine its individual character and its relation to the arc as a whole. The study of the Marianne arc, which is in an extremely youthful stage, has brought out the fact that this arc is made up of three distinct zones from front to back, and that it betrays a no less marked differentiation when examined in a direction from end to end. At its southern end it is indicated merely by a raised atoll, that of Feys.

⁵ H. A. Brouwer: The horizontal movement of geanticlines and the fractures near their surface. Jour. Geol., vol. 29, 1921, pp. 560-577. Fractures and faults near the surface of moving geanticlines. II. Abnormal strikes near the bending-points of the horizontal projection of the geanticlinal axis. Proc. Roy. Acad. Sci. Amsterdam, vol. 25, 1922, pp. 229-334.

⁶ Earth evolution and its facial expression. Macmillan, 1921, pp. 139-142.

⁷ W. H. Hobbs: Les guirlandes insulaires du Pacifique et la formation des montagnes. Conférence faite à la Sorbonne le 29 avril, 1922. Ann. de Géog., vol. 31, 1922, pp. 485-495.

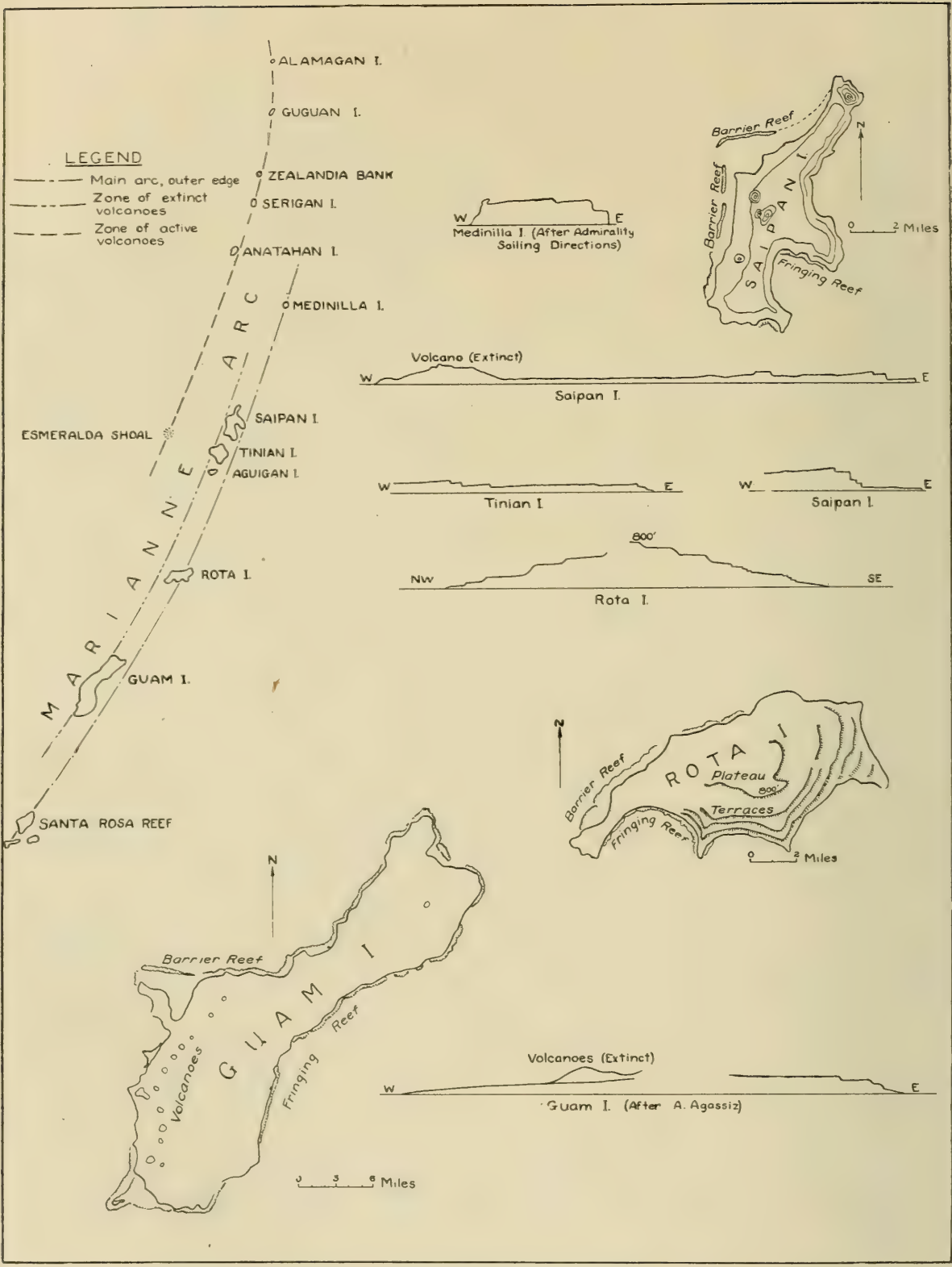


FIGURE 2.—Characters of the Islands composing the Marianne Arc

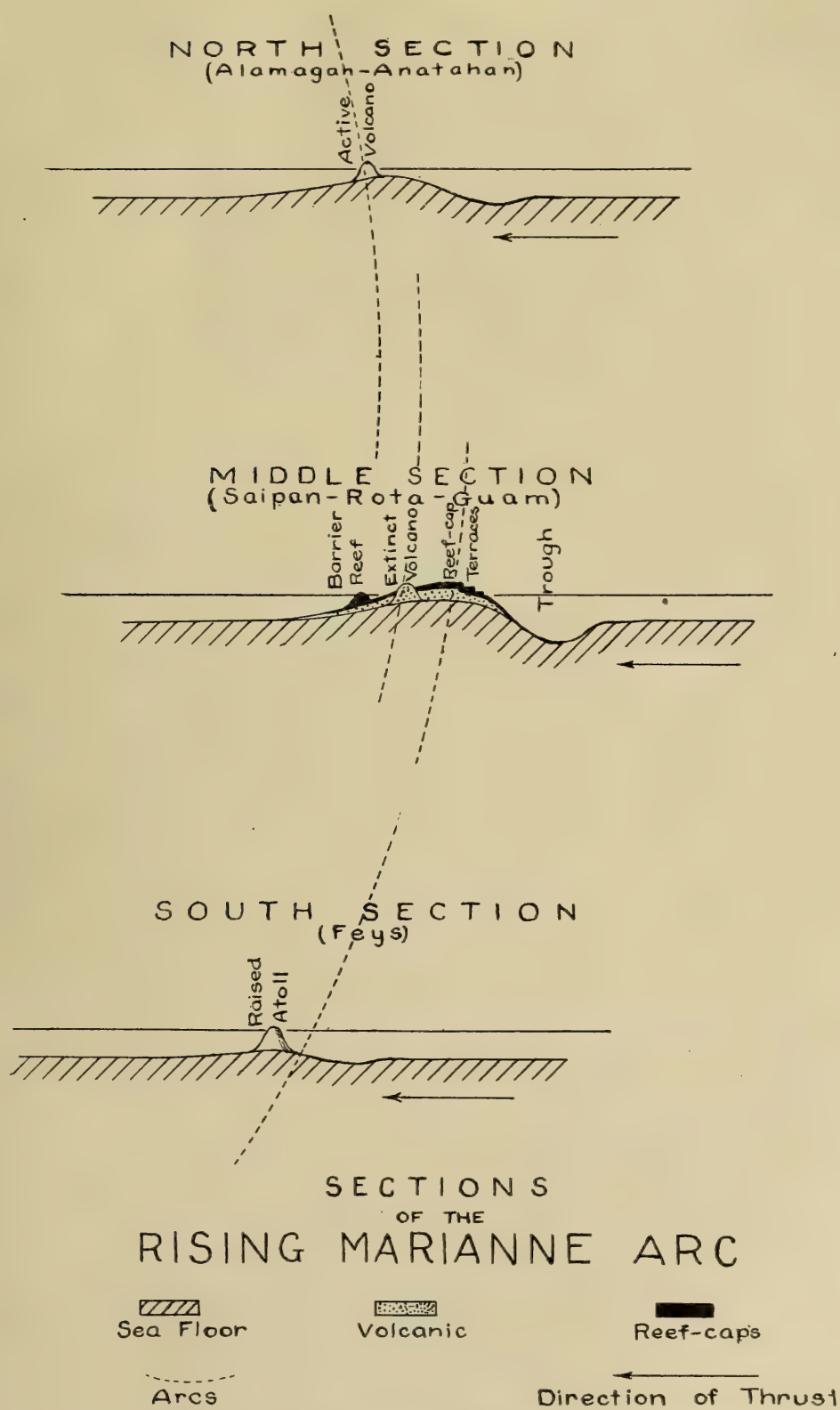


FIGURE 3.—Comparison of the different Sections of the Marianne Arc

Within its middle and most mature portion it shows on its outer side elevated reef terraces with the islands as a whole sloping toward the interior of the arc. On the western margin of this zone are found extinct, though recent, volcanoes. Toward the north the arc is continued by a line of active volcanoes, but these are aligned on a curve which is interior to that of the main line of islands (figure 2). Thus differentiated, the perfection of curvature which characterizes the Marianne arc appears quite remarkable, as can be seen from the large scale hydrographic map of the region. The contrasted characters of the southern, medial, and northern sections of this arc are set forth in figure 3.

CROSS-SECTION OF THE APPALACHIANS IN SOUTHERN
NEW ENGLAND ¹

BY J. B. WOODWORTH

(Read before the Society December 28, 1922)

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INTRODUCTION

The time has not yet arrived for the construction of a determined geological cross-section of southern New England from the Hudson River on the west to the sea on the east coast of Massachusetts. Partial sections have been published for the western part of Massachusetts, including the Triassic area of the Connecticut Valley; detailed local sections have been made by Perry about Worcester, Massachusetts, and detached sections have been put forth to illustrate the structure of the Boston and Narragansett areas, in eastern Massachusetts. Pumpelly, Wolff, and Dale have given a section of Greylock Mountain.

Professor Emerson, in his latest map of Massachusetts, refrained from publishing a cross-section of the State, probably because of the difficulty

¹ Manuscript received by the Secretary of the Society May 26, 1923.

This paper is one of a series composing a "Symposium on the structure and history of mountains and the causes of their development."

of doing so in the region of schists occupying the middle area between Worcester and the Connecticut boundary. Here the question of the geological age of the schists regarded by Emerson as mainly Carboniferous still provokes an inclination on the part of other geologists to regard the low-lying dip of the schistosity as an indication of a Precambrian age.

What follows in the statements of the present writer must therefore be understood as made with full understanding of current opinion regarding the age of the rocks in that part of the State. From the point of view of this paper, the acceptance of either view affects chiefly the question of the amount of erosion and uplift of the rocks in the Worcester area during and since the mountain-building of Paleozoic time. If, as Emerson contends, the schists are Carboniferous, the vertical uplift relative to sections on the west and east has been less probably by a few thousand feet than would be the case if the rocks now at the surface are of Precambrian age. Not being prepared to confirm or deny the Carboniferous age of the schists in question, the writer can only consider the consequences of both structural views on the problem here dealt with.

WESTERN, CENTRAL, AND EASTERN SECTIONS

THE WESTERN SECTION

On the west, the section ends rather abruptly against the little or not at all folded Paleozoic rocks of eastern New York immediately west of the Hudson River. On the east, the folded and faulted structures of Massachusetts undoubtedly continue eastward beneath the sea-floor, without an assignable limit in that direction. In the middle part of Massachusetts lies a belt of gently inclined crystalline schists, sharply folded at intervals, or characterized by a narrow folded belt of Carboniferous sediments, as in the Worcester basin on the eastern limit of the flattish belt of schistose rocks.

On the extreme west, in the Hudson Valley and at various points, westward overthrusting of strata as old in age as the Ordovician has long been known. This forms a segment of the extended line of Appalachian structures displaying the westward overthrust on the western side of that mountain system, which has given rise to such explanatory phrases as "westward thrust from the Atlantic basin," implying that the middle and eastern parts of the Appalachians participated in the same movement and displayed the same westward overturning of folds and shearing movements.

To the east of these westward thrusts, in the Taconic Range, the Greylock Mountain section, as drawn by Pumpelly, Wolff, and Dale, shows the

metamorphosed strata thrown into anticlines and synclines whose axial planes display some diversity of dip, often westward, though more pronouncedly eastward because of a westward overthrust.

THE EASTERN SECTION

The Worcester district.—To the east of the central tract of little disturbed schists, eastward overturning becomes pronounced in the Worcester district, as exhibited in Perry's local section. The basins of Carboniferous and older rocks occupying the coastal lowland form parts of an arcuate system of large folds concave toward a point near the heel of Cape Cod, with a consequent turning of the line of the geological cross-sections to the southeast.

The Boston area.—In the Boston area the plan of the folding is complicated by a fault along the northern border through Medford. The sediments in the basin are accordingly turned up and locally overthrown, as shown by W. M. Davis, at Maplewood, where the Roxbury conglomerate is cut out by an apparent upthrust, if not overthrust, of the crystallines and the Lynn volcanics to the north of the fault.

In the Cambridge argillites of the Mystic River quarries in Somerville, overthrusting to the southeast is a pronounced feature in the detailed structure of the argillite. Overthrusting in a selective manner on apparently then unconsolidated clays also set in early, so as to produce a zone of overturned and recumbent contortions about 30 feet thick in the existing section. This movement was followed, after the intrusion of "gray" dikes and sills, by thrust-planes on which the total movement probably amounts to several hundred feet in the exposed section, single thrusts measuring as much as 140 feet.

Along the northern flank of the anticline of Roxbury conglomerate in Brighton and Chestnut Hill, overthrusts with a southerly, large component of motion have long been well known. Thus the prevailing overthrusting motion in the Boston basin is southward across the strike, certainly not "away from the Atlantic basin."

The Narragansett area.—The large structural feature of the eastern arm of the Narragansett coal basin in Massachusetts is decidedly symmetrical on either side of the central Taunton syncline, but in the north-western corner of the basin, about North and South Attleboro, the apparent structure about the Hoppin Hill granite block and its inclosing Lower Cambrian formation is that of a flattened-down fan structure of red Carboniferous beds overthrown southward in a horseshoe-shaped fold and overthrust upon the folded Coal Measures on the southern and south-eastern border of this tract. In marked contrast with this disturbance,

there is, if the structure be understood by the writer, a pronounced westward overturn of apparent folds, along the western side of Narragansett Bay from Providence southward. If, however, one adopt the view that this section is not composed of isoclinal folds, then the beds may be regarded as simply dipping eastward into the basin. On the other hand, the cross-section of Prudence Island shows a syncline with vertical beds on its eastern side and only moderately steep dips on the western side. Accordingly, the general structure of the Narragansett area is somewhat diverse and exhibits more of local control than of a general widespread direction in the overturning of folds.

PLAN OF THE SECTIONS AS A WHOLE

GENERAL STATEMENT

The impression one receives on the whole of these folded Carboniferous strata of southeastern Massachusetts is against the idea of an overthrust from the Atlantic border inward toward the central axis or western border of Appalachian structure. The general direction of overturning and overthrust is toward, rather than away from, the ocean basin on the east and south. It is obvious that the Boston-Providence area is not a part of the typical Appalachian folded structures along the western margin of New England and the States on the south, and from this limitation it is inferred that maximum overthrust toward the Atlantic would be found along the eastern side of this region; hence that somewhere in that direction yet more pronounced southeastward overthrusting may have taken place.

The conventionalized view of the geological section across Massachusetts thus presents itself to us as one having a central tract of nearly flat-lying crystalline schists, certainly as old as the Carboniferous and thought by some to be yet older and probably of Precambrian age, to the east and southeast of which there is a region of recognizable overthrusting toward the Atlantic, while to the west of the schists overthrusting is to the west and is of the Appalachian type. In this view the section presents a central axis of little horizontal motion relative to the margins as they are now shown. This central axis of least horizontal compression is highly crystalline and must have been at one time under a thick cover of superincumbent rock, whatever be the age of the schists now at the surface. If the rocks of this axis are of Carboniferous age, the surface of the Precambrian schists is presumably not far below, since the Carboniferous here can not be very thick; if, however, the schists now at the surface are of Precambrian age, then the former Precambrian surface here rose dur-

ing Paleozoic times farther above the present surface than elsewhere in the State. In the central part of the Narragansett basin, in the axial center of the Taunton syncline, the structure indicates a maximum depth of about two miles of sediments, measured to the floor of the Carboniferous sediments—involving a deleveling and deformation of the Mississippian land surface which took place during Pennsylvanian time, and the later episode of Appalachian folding. On the west in the Taconic Range, where the time of folding is not yet clearly determined, the Precambrian surface is probably not at so low a depth below present sealevel.

The cross-section of the formations from the Hudson, on the west, to Cape Cod, on the east, shows (1) on the extreme west the well known Appalachian geosyncline of Cambrian to Devonian time; (2) a central tract relatively stable during Paleozoic time and with a minimum of compression and folding, made up of schists that are either of Carboniferous or Precambrian age; and (3) an eastern segment. The last named consists of folded patches of Cambrian strata intruded by granodiorites about Boston, and of Devonian at Danvers, Massachusetts. The whole segment was probably mountain-built in mid-Devonian time and intruded by granitic batholiths, followed by erosion to a low relief. At the beginning of Alleghenian time crustal movement and igneous eruptions set in and the area became the seat of a very thick series of freshwater conglomerates and tillite (eastern part of Boston area), and finally the entire segment was involved in the Appalachian folding and overthrusting movements about the close of the Paleozoic. The existing basins of conglomeratic sediments indicate the breaking up of a land surface at the close of the Mississippian, accompanied by vulcanism and the uplift of adjoining areas of erosion outside of the existing basins of deposition. The increased coarseness of the sediments (conglomerates) southward in the Narragansett area (toward Newport) and eastward in the Boston area shows a derivation of the material from the east and south, or in general from a land to the southeast, pointing to steep stream gradients in that direction sloping northwestward from highlands beyond but near the present border of the Atlantic coast. Thus the eastern limit of the Acadian structure (New England States and the Maritime Provinces of Canada) is not shown in southeastern Massachusetts. What the direction of overturning is in that lost land off the present coast (Schuchert's Novascotica) is not directly known.

LOST LAND OFF THE COAST

The conglomerates of Pennsylvanian age in the southern parts of the Narragansett area contain pebbles of quartzite or sandstone with an

abundance of late Cambrian brachiopods, and two pebbles have been found, one *in situ*, the other in the drift on Marthas Vineyard, carrying a *Spirifer* like that of the Lower Devonian Chapman sandstone of Maine. From this fragmentary evidence it is inferred that strata as old as the Lower Devonian were exposed to erosion in Alleghenian time in this lost land, now a part of the existing coastal shelf.

The westwardly dipping schists along the Atlantic coast from southern Maine southward across Maryland and North Carolina, as seen beneath the cover of Mesozoic and Cenozoic strata along the inner edge of the coastal plain, support the view of a widespread overturning of structure toward the southeast, or, in other words, toward the present Atlantic basin. This is in marked contrast with the general westward overturning of structure on the western border of the Appalachian mountain belt, whatever difference there may be in the age of the diastrophic movements.

In the eastern part of the section across Massachusetts, intrusive and extrusive phenomena took on a noticeable development during the later Paleozoic phases of deformation. Therefore, during Pennsylvanian time, erosion and deposition were introductory to the mountain-building and vulcanism in this Acadian field.

On the Avalon peninsula, at the southeastern extremity of Newfoundland and eastward of the line of strike of the folded Carboniferous strata of Cape Breton and southeastern Massachusetts, Cambrian strata dip gently seaward along the shore of Marys Bay. These beds appear to form a remnant of the tilted Paleozoic strata on the eastern border of the Acadian mountain belt, from southern New England northeastward through southern Newfoundland. The New England section of Acadian structure, from the mouth of the Hudson River eastward to the head of Buzzards Bay, is cut off on the south by the sea. South of this area, the southern equivalent of Acadia, the eastern portion of the Appalachian mountain belt, lies concealed beneath the Mesozoic and later strata of the coastal plain. From Alabama to Newfoundland the curvilinear strikes of the geological structure are reflected in the great curving bights of the coast and its projecting capes. The Precambrian and all later Paleozoic rocks bear one pervading sinuous structure, impressed on them in the closing Paleozoic episode of mountain-building, as if the ranges were shortened from northeast to southwest by gigantic bendings in a horizontal plane transverse to their longitudinal extension. These great bends in the larger structure of the eastern border of North America, alternately northwestward and southeastward, characterize a complex Paleozoic mountain system in which the western margin displays quite uniformly a westward outflow of rock, while its eastern margin—imper-

fectly shown because largely concealed beneath the coastal plain on the south and beneath the sea on the north—exhibits an eastward overturning, as if toward its eastern border.

THE CENTRAL REGION

The central region in New England is not one of engulfment of the newer and highest strata in the folded system, but, on the contrary, a tract in which the Precambrian is about as high as elsewhere. South of New York City, in the area of crystalline rocks of the piedmont region lying between the typical Appalachian structures along the western side of this mountain system and the place beneath the coastal plain in which one would expect to find the extension of the Carboniferous folds of eastern Massachusetts and Nova Scotia, the local structures indicate that the central axial part of the range brought ancient rocks to high levels. Furthermore, the general plan of the cross-section of the foldings shows, along with some shifting of the sites of geanticlines and neighboring geosynclines, a central tract of uplift and erosion of older rocks bordered on one or both sides by geosynclinal troughs of deposition whose final structural expression exhibits outthrust toward the outer borders of the compressed region. This fan-shaped structure is, however, not without much diversity where igneous intrusions have appeared during or just after the episodes of folding. For this reason large tracts of Precambrian rocks make the axial areas of the Acadian range, and thick sections of Paleozoic strata, including Carboniferous formations, sometimes with coal, now lie here and there on or near the margins of the complex mountain structure. The greater Appalachian system in eastern North America has gained the reputation of being wholly overthrust westward because its western border, exhibiting that structure, is everywhere exposed to examination, and because its eastern border is largely concealed or has not been considered in the description of its broad physiognomy. So far as we are permitted to observe the eastern border of the Acadian area, strata varying in age from the Carboniferous downwards to the Precambrian are at the present surface above sealevel, and eruptives of Carboniferous or immediately post-Carboniferous age play a larger rôle in the surface exposures than is the case west of the Connecticut Valley. One must conclude, therefore, that volcanic phenomena prevailed on the eastern or southern flanks of the mountain system in Pennsylvanian times, in contrast with the paucity or absence of eruptives of this date on the western overthrust belt of the same system. A like one-sidedness in the distribution of igneous intrusions appears to characterize the less well

exhibited mountain structures of the Middle or Upper Devonian of the Acadian region. The prevailing tendency of volcanoes to break out on the coastal slope of the great Tertiary ranges of the globe finds in this distribution some analogy and suggests that the North Atlantic basin was forming, if not in existence, beyond the present continental border, despite the fact that we find no evidence of it as a great north-south trench on the border of the continent until after the dawn of the Cretaceous period.

THE TRIASSIC NORMAL FAULT BLOCKS

The normal faulting, which rose to its maximum displacements after the Newark formations of Upper Triassic time, has raised and lowered differentially portions of the Paleozoic strata in Massachusetts. As Barrell pointed out, the block between the Connecticut and the Hudson rivers has the appearance of having been arched up midway between its depressed edges on the east and west. This is especially true of the cross-section through the State of Connecticut to the western border of the Triassic area in southeastern New York and northeastern New Jersey. According to conservative estimates of the downthrow of the Triassic strata, where greatest, in New Jersey and Connecticut along the western and eastern boundary faults respectively of this block, the relative displacement appears to be as great as two miles vertically. Some part or all of this vertical displacement may be attributed to the relative uplift of the Paleozoic and older rocks on the outer sides of the block in question. What we note is that the region of flat-lying schists in central Massachusetts stands relatively higher today than it did in mid-Triassic time, when compared with the sedimentary base in Newark time (Upper Triassic).

The eastern limit of the wide fault block to the east of the Connecticut Valley would seem to be found in the bounding fault of the Triassic area of the Bay of Fundy and the New Brunswick shore. Erosion has probably very largely removed the Triassic from a former extension southward over the floor of the Bay of Maine. The southwestward continuation of the fault along the west side of the Bay of Fundy to Cape Cod Bay is a matter of conjecture, supported only by the remarkable depression of the bedrock surface off the eastern coast of northeastern Massachusetts and by the manner in which the break in the surface is staked out by the marked earthquakes of colonial times at Plymouth in 1638, Newbury in 1727, and the vicinity of Scituate in 1755—three valid symptoms of a fault existing along or off that coast.

SUMMARY

In this generalized view of the cross-section of the Appalachian diastrophic effects in southern New England, the middle parts exhibit no clear signs of engulfment between overturned and outthrust marginal folds, such as Holmquist invoked in his ideal sketch of a collapsed geosyncline. On the contrary, the middle portion (New Brunswick geanticline of Schuchert) stands relatively high in the closing stages of the two geosynclines of deposition (Saint Lawrence and Acadian) on either side of it and was relatively stable and unyielding during the subsequent phase of strong compression and collapse, its movements, if anything, being then upward rather than downward.

As I now see it, the potent factor in mountain-building and vulcanism lies in the depths beneath disturbed belts of mountain systems, wherein crust and magma move under the control of a vertical force, of which ever-present gravity and changes of temperature, however caused, are components, having diverse effects at the surface of the earth under the secondary influences of deposition and erosion. An upstanding belt of old rocks, flanked on one or both sides by detrital troughs of now collapsed strata more or less overturned from the median region, and here and there invaded by metamorphosing igneous intrusions, shown in the cross-section of a mountain system of folded and locally overthrust strata and basal crystalline schists, strengthens the writer's confidence in the doctrine of isostasy as a statement of the working conditions under which mountain-building went forward in the Appalachian region after the initial geanticline and geosynclines were produced to set in motion a transfer of load by erosion and deposition. Once it is recognized that the historical "Appalachian geosyncline" of Dana, first recognized by James Hall of Albany, is a lateral affair in a broad mountain-built zone, the almost complete lack of igneous intrusives in that portion of the section, does not exclude the rôle of magmatic movements in the problem of Appalachian mountain-building in its broader sense, and viewed in its full scope the Appalachians find their counterparts in the great Cordilleras of the Pacific region.

STRUCTURE OF THE ROCKY MOUNTAINS IN IDAHO
AND MONTANA¹

BY GEORGE ROGERS MANSFIELD

(Presented before the Society December 28, 1922)

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INTRODUCTION

Most of the writer's experience with Rocky Mountain structure has been gained in eastern Idaho in connection with the United States Geological Survey's study of the western phosphate field, but some years ago he conducted a series of field parties from the Harvard University Summer School in southwestern Montana. He therefore feels some measure of acquaintance with the structural conditions in that State as well. The

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remarks that follow are based chiefly on work in Idaho, but some mention is made of Montana and of other regions for comparison.

Detailed or semi-detailed study has been made of three separate districts in eastern Idaho, namely: (1) the Fort Hall Indian Reservation, (2) an area comprising 7 quadrangles lying about 15 miles east of the Fort Hall Indian Reservation and extending to the southeastern corner of the State, and (3) an area lying immediately west and south of the Teton basin. Since some of the structural features of these areas have already been described elsewhere, only brief reference need be made to them here, and the paper will be devoted chiefly to broader aspects of mountain structure suggested by the detailed studies.

FORT HALL INDIAN RESERVATION ²

The Fort Hall Indian Reservation comprises an area of about 800 square miles in Bingham, Bannock, and Power counties and includes parts of several mountain ranges. The older sedimentary rocks, of Paleozoic and Mesozoic age, which make up these ranges are overlapped by Tertiary and Quaternary sediments and by igneous rocks as the ranges descend northward to the Snake River plain.

The chief mountain-building activity in the reservation occurred after the deposition of the Jurassic beds, the latest Mesozoic rocks there exposed, and before the deposition of the Tertiary rocks, which are believed to be of Pliocene age, but these last have been affected to a certain extent by subsequent movements. The major deformation was undoubtedly a part of the great Laramide Revolution. The Paleozoic and Mesozoic strata have been folded, locally with considerable intensity, and the folds, which have in general a northwesterly trend, have been inclined or even overturned northeastward. Transverse folding at right angles to the general trend is also present. Many of the folds are broken by thrust-faults and one overthrust-fault of considerable magnitude, the Putnam overthrust, has been recognized and described. Rock slices or cappings in the Portneuf Range, in the southeastern part of the reservation, which represent parts of an overthrust block now detached by erosion, are believed to be associated in some way with this great overthrust. Similar rock slices in the northern part of the Bannock Range, farther west, and in the unnamed range east of Bannock Valley, in the southwestern part of the reservation, may also be connected with this overthrust, but con-

² G. R. Mansfield: Geography, geology, and mineral resources of the Fort Hall Indian Reservation, Idaho, with a chapter on water resources by W. B. Heroy. U. S. Geol. Survey Bull. 713, 1920.

siderable areas which intervene have not yet been mapped, and in the mapped areas the older rocks and structures are largely concealed by younger sediments and by igneous rock. Tensional faulting of later date has also been recognized and described. These structural features are all illustrated in the geologic map and structure sections that accompany the report cited.

AREA OF SEVEN QUADRANGLES

Seven quadrangles in the vicinity of the Wyoming border have been studied rather intensively. These include the Montpelier 30-minute quadrangle at the south and six 15-minute quadrangles, namely, the Slug Creek, Crow Creek, Lanes Creek, Freedom, Henry, and Cranes Flat quadrangles. Together they occupy parts of Bingham, Bonneville, Caribou, and Bear Lake counties and comprise an area of about 2,000 square miles. Preliminary accounts of some of the structural features of this area have already appeared in connection with official reports or in special papers,³ to which the reader is referred for available details. A comprehensive report covering the entire area has been prepared for publication as a professional paper of the United States Geological Survey.

The area contains a number of mountain ranges, members of the Idaho-Wyoming chain, that have been complexly folded and faulted, and the folds show a pronounced curvature in trend from a direction a little east of north in the Montpelier quadrangle to northwest in the more northerly quadrangles. Some of the folds exceed 50 miles in length and 3 miles in breadth, the more important being synclinoria with relatively narrower intervening anticlines or anticlinoria. Usually they are unsymmetrical and inclined or even overturned eastward or northeastward. The axes for long distances are nearly horizontal or slightly undulatory, due to the presence of relatively broad and low transverse folds, and the pitch is gentle, generally toward the north or northwest.

In the last paper cited above the writer has given descriptions of the

³ H. S. Gale and R. W. Richards: Preliminary report on the phosphate deposits in southeastern Idaho and adjacent parts of Wyoming and Utah. U. S. Geol. Survey Bull. 430, 1910, pp. 457-535.

R. W. Richards and G. R. Mansfield: Preliminary report on a portion of the Idaho phosphate reserve. U. S. Geol. Survey Bull. 470, 1911, pp. 371-451.

R. W. Richards and G. R. Mansfield: Geology of the phosphate deposits northeast of Georgetown, Idaho. U. S. Geol. Survey Bull. 577, 1914.

R. W. Richards and G. R. Mansfield: The Bannock overthrust, a major fault in southeastern Idaho and northeastern Utah. Jour. Geol., vol. 20, 1912, pp. 681-707.

G. R. Mansfield: Igneous geology of southeastern Idaho. Bull. Geol. Soc. America, vol. 32, 1921, pp. 249-266.

G. R. Mansfield: Types of Rocky Mountain structure in southeastern Idaho. Jour. Geol., vol. 29, 1921, pp. 444-468.

more important structural types of the area. These need not be repeated here. Suffice it to say that they include swallowtail folds, drag folds, fan folds, both upright and inverted, a transverse fold passing into an overthrust fault, an imbricated and folded overthrust fault, and horst and graben structure.

TETON BASIN

The Teton Basin area, which lies about 40 miles north of the Freedom quadrangle, along the Wyoming border, comprises an area of approximately 300 square miles in Madison, Teton, and Bonneville counties. The eastern side of the basin is formed by the west flank of the Teton Range and the western side is bounded by the Big Hole Mountains, which include a small coal-bearing area known as the Teton coal field. These mountains, like those in the other two areas previously mentioned, have a northwesterly trend and show unsymmetrical form with inclination or overturning toward the northeast. A number of thrust-faults traverse the area. Two of them, the Absaroka and Darby faults, have considerable magnitude. An outlying mass of the Darby overthrust block, separated from it by erosion, lies in front of the main block and testifies to the gentle inclination of the fault-plane, which is elsewhere concealed by debris from the overlying block. A general account of this area, including additional structural details, has already been published.⁴

IDAHO AND THE NORTHERN ROCKIES

It has been shown that eastward inclined folds and eastward overthrusts are characteristic of the Rocky Mountains in Idaho. Similar structures have been observed by the writer in Montana, and it is believed that they are fairly characteristic of the northern Rockies as a whole. Certainly, remarkable eastward overthrust faults have been recognized at a number of places from Canada as far southward as Utah and Colorado. These may now be briefly reviewed (see figure 1).

THRUST-FAULTS OF THE NORTHERN ROCKIES

The Lewis overthrust, first described by Willis⁵ and later mapped by Campbell, has a minimum horizontal displacement of 15 miles. It has a sinuous course for many miles along the Rocky Mountain front in

⁴ G. R. Mansfield: Coal in eastern Idaho. U. S. Geol. Survey Bull. 716-f, 1920.

⁵ Bailey Willis: Stratigraphy and structure, Lewis and Livingston ranges, Montana. Bull. Geol. Soc. America, vol. 13, 1902, pp. 331-336.

M. R. Campbell: The Glacier National Park. U. S. Geol. Survey Bull. 600, Pl. 13, 1914.

northwestern Montana and has been traced northward into Canada.

Near Philipsburg, Montana, a thrust-zone comprising two principal and several minor faults has been described by Calkins,⁶ who considers it probable that this zone is a southerly continuation of the Lewis overthrust. According to Calkins, this fault-zone is an early tectonic feature, since the fault-planes have been folded and dislocated by normal faults to nearly the same extent as the rock strata.

The *Lombard overthrust*, as described by Haynes,⁷ has a length of about 13 miles and a maximum displacement along the fault-plane of about 2 miles.

The *Beartooth fault*, along the northeastern border of the Beartooth

⁶ W. H. Emmons and F. C. Calkins: *Geology and ore deposits of the Philipsburg quadrangle, Montana*. U. S. Geol. Survey Prof. Paper 78, 1913, pp. 146-150.

⁷ W. P. Haynes: *The Lombard overthrust and related geological features*. *Jour. Geol.*, vol. 24, 1916, pp. 269-290.

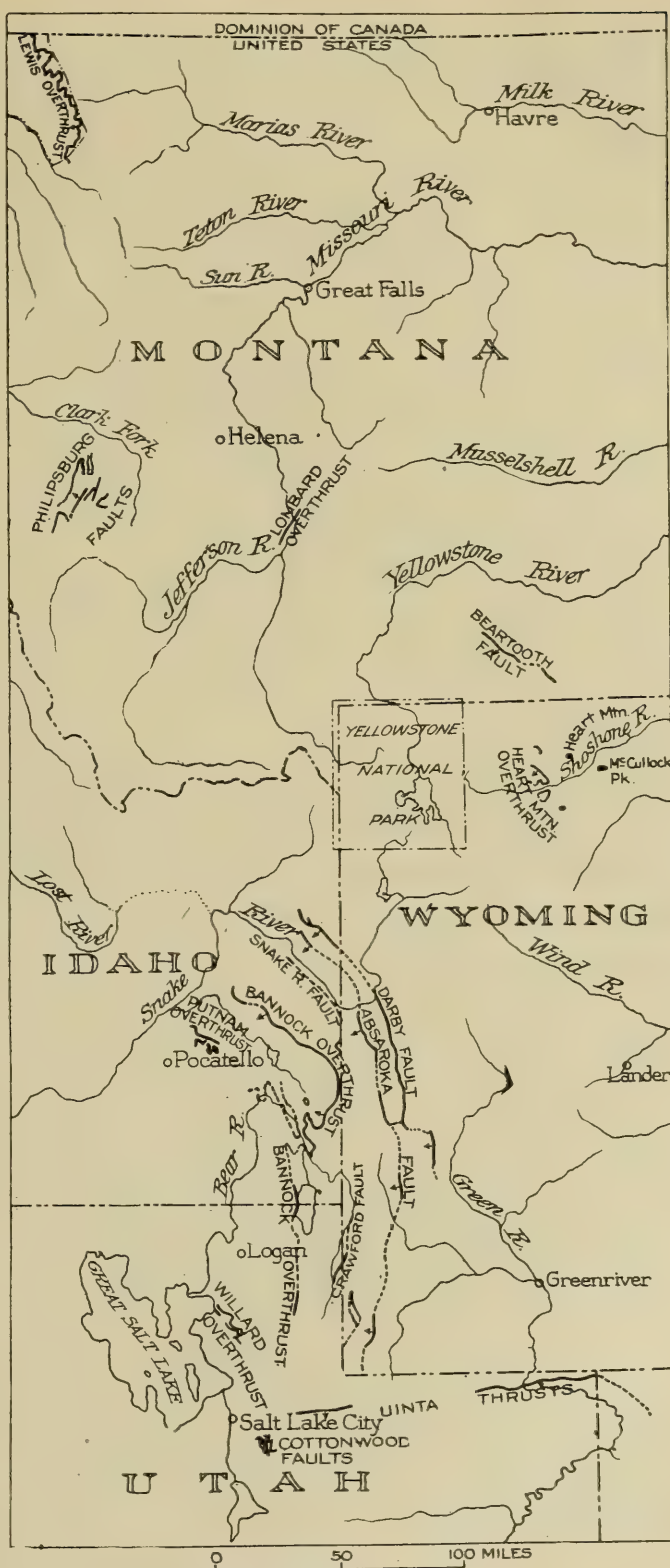


FIGURE 1.—Distribution of the known great Overthrusts in the northern Rocky Mountains

Mountains, has a length of about 35 miles as mapped by Calvert.⁸ It was not at first considered as an overthrust, but its relationship to zones of overthrusting farther southeast makes this interpretation highly probable.

The *Heart Mountain overthrust*, first described by Dake⁹ and later by Hewett, has a minimum horizontal displacement of 28 miles and should be traceable over the entire eastern edge of the Absaroka Range perhaps for 125 or 150 miles.

The *Darby fault*, as mapped by Schultz,¹⁰ has a length of about 125 miles and a horizontal displacement perhaps greater than 15 miles.

The *Absaroka fault*, as mapped by Veatch¹¹ and Schultz,¹² has a known length of approximately 200 miles. Its zone of displacement may exceed 25 miles in breadth and its throw (stratigraphic?), like that of the Darby fault, is said to exceed 20,000 feet.

The *Medicine Butte* and *Crawford faults*, as mapped respectively by Veatch¹³ and by Gale and Richards,¹⁴ in southwestern Wyoming and in northeastern Utah, are overthrusts on a smaller scale than most of the preceding.

A thrust-fault some 30 miles in length has been recognized by Schultz and Richards¹⁵ along Snake River, but little is known of its displacement.

The *Bannock overthrust*, as mapped, is about 270 miles long and has a maximum displacement perhaps greater than 35 miles. It seems possible that the Bannock overthrust and the Putnam overthrust, to which reference has already been made, may prove to be connected.

The *Willard overthrust*, as described by Blackwelder,¹⁶ is about 22 miles long and has a maximum displacement of at least 4 miles. It is exceptional for the Rocky Mountain region, in that the inclination of its plane is apparently eastward instead of westward.

⁸ W. R. Calvert: Geology of the upper Stillwater basin, Stillwater and Carbon counties, Montana. U. S. Geol. Survey Bull. 641, 1917, pp. 199-214.

⁹ C. L. Dake: The Hart Mountain overthrust and associated structures in Park County, Wyoming. Jour. Geol., vol. 26, 1918, pp. 52-53.

D. F. Hewett: The Heart Mountain overthrust, Wyoming. Jour. Geol., vol. 28, 1920, pp. 536-556.

¹⁰ A. R. Schultz: Geology and geography of a portion of Lincoln County, Wyoming. U. S. Geol. Survey Bull. 543, 1914, pp. 84-85, map.

¹¹ A. C. Veatch: Geography and geology of a portion of southwestern Wyoming. U. S. Geol. Survey Prof. Paper 56, 1907, pp. 109-110.

¹² Idem., p. 87, and U. S. Geol. Survey Bull. 680, 1918.

¹³ Idem., pp. 111-113.

¹⁴ Op. cit., p. 515.

¹⁵ A. R. Schultz and R. W. Richards: A geologic reconnaissance in southeastern Idaho. U. S. Geol. Survey Bull. 530, 1913, p. 277 and pl. vi.

¹⁶ Eliot Blackwelder: New light on the geology of the Wasatch Mountains, Utah. Bull. Geol. Soc. America, vol. 21, 1910, pp. 517-542.

In the Cottonwood district, Utah, the *Alta* overthrust has been recognized by Hintze, Butler, and Loughlin and more recently it has been studied by Calkins. This fault dips eastward but steepens downward and probably passes the vertical in places. Calkins¹⁷ believes, mainly from the relations of drag folds, that the upper block moved eastward and that the original dip of the thrust-plane was westward.

Along the north base of the Uinta Mountains two important zones of thrusting have been observed. As described by Schultz,¹⁸ the more westerly of these zones is exposed for 20 miles and the more easterly, the great *Uinta fault*, first recognized by geologists of the King and Powell surveys, is 80 miles or more long. In both instances the forces which produced the dislocation appear to have acted from the south or southeast. The stratigraphic interval produced by these faults is not less than 20,000 feet. Most of this seems to be vertical, though there may be also a horizontal displacement of considerable magnitude.

RELATIVE MAGNITUDE AND IMPORTANCE OF OVERTHRUSTS

The overthrusts above described vary in length from a few miles to nearly 300 miles. The breadth of their respective areas of dislocation varies from 2 or 3 miles to nearly 40 miles. They differ also in the stratigraphic intervals which they produce. Some of these apparent differences are probably due to lack of present knowledge, but without doubt some of the faults, such as the Lewis, Bannock, and Absaroka overthrusts, are displacements of a larger order than some of the others.

RELATIVE AGES OF OVERTHRUSTS

It has not been possible thus far to fix the geologic age of many of the overthrusts mentioned above more closely than to state that they are pre-Tertiary (Philipsburg quadrangle), late Cretaceous, or early Tertiary, or post-Cretaceous. For a few the information is a little more definite. For example, Willis, on the basis of both structural and physiographic evidence, ascribes mid-Tertiary age to the Lewis overthrust. Later, mostly unpublished work by geologists of the Federal Survey, in regions east of the mountains not visited by Willis, shows that this fault is either of late Eocene or early Oligocene age. The Beartooth fault is indicated as of post-Fort Union age. Hewett shows that the Heart Mountain over-

¹⁷ Personal communication.

¹⁸ A. R. Schultz: A geological reconnaissance of the Uinta Mountains, northern Utah, with special reference to phosphate. U. S. Geol. Survey Bull. 690, 1919, pp. 69-74; see also U. S. Geol. Survey Bull. 702, 1920, pp. 43, 46, and pl. i.

thrust is of later age than Horizon A of the Bridger formation and is therefore not earlier than middle Eocene nor later than Oligocene.

One fact that appears to be established by reviewing the age relationships of the various thrust-faults is that these faults were in all probability not synchronous. This fact indicates that the compressive stresses that produced the overthrusts were maintained over a considerable period and that they found relief at more or less distinct, successive intervals—a conclusion to be naturally expected, in view of the greatness of the region affected and of the tremendous stresses involved.

POSSIBLE RELATIONSHIPS OF OVERTHRUSTS

In a valuable paper on structural conditions in central and western Montana, Thom¹⁹ mentions briefly most of the overthrusts above reviewed. He thinks that the continuity of the mountain ranges, the relative topographic position of the terranes involved, and the observed magnitude of the horizontal displacements indicate that these faults have a common origin and are parts of a continuous major fracture. He depicts central Montana as a region where the simple overthrust seen in the Canadian Front Range gives place to more complex structural conditions probably because the edge of the overthrust sheet there impinged on older east-west uplifts and was disrupted by them. According to Thom's view, waves of deformation and intrusion, which began on the Pacific coast in Upper Jurassic time, affected areas progressively farther east, but were not vigorously active in the Front Range until the Upper Cretaceous.

Kober²⁰ regards the eastern ranges of the Rocky Mountains northward from the Yellowstone National Park as border chains of a great geosyncline, which have been thrust forward on a foreland of older and more rigid rocks. His idea of the structure of border chains, derived from a study of the Alps,²¹ is that of a highly folded and faulted mass, parts of which have been torn from their foundations, piled up on each other to a greater or less extent, and moved bodily forward toward or on the foreland. He accounts for the difference in the aspect of the eastern chain in Montana and Colorado by assuming that the mountains in Colorado east of the Wasatch Range, which he calls the Colorado plateaus and the pre-Cordillera, represent earlier folded and eroded mountains, which had become incorporated in the foreland and were little, if any, affected by

¹⁹ W. T. Thom, Jr.: The relation of deep-seated faults to the surface structural features of central Montana. Manuscript submitted for publication to Am. Assoc. Petrol. Geols., November, 1922.

²⁰ Leopold Kober: *Der Bau der Erde*. Berlin, 1921, pp. 160-161.

²¹ *Op. cit.*, pp. 86-89.

the supposedly later orogenic forces which produced the mountains farther north.

In the paper on "Types of Rocky Mountain structure" previously cited the writer has shown that certain Alpine characteristics are present in the mountains of southeastern Idaho. The presence of great overthrusts in the Rocky Mountain region points to additional similarities of structure, but thus far nothing comparable in complexity with the more highly developed Alpine structures—the so-called *decke*—has there been recognized.

Thom, in his consideration of conditions in central Montana, seems to assume that the movement of the disturbed parts of the outer earth's shell has all been eastward, but that some parts were more retarded than others. The evidence presented on figure 1 shows that there were at least two well defined directions of movement—an easterly movement, which obtained as far south as the southwest corner of Wyoming and parts of Utah immediately west, and a northerly movement, represented by the zones of thrusting and faulting along the north border of the Uinta Mountains. The change of direction of movement is very abrupt, forming nearly a right angle. The faults of the Cottonwood district, which are very complex, appear to occupy a strategic position at the apex of the angle. It is possible that the direction of faulting along the Uintas may be due merely to the resolution of the generally eastward-acting forces which there impinged on an earlier opposing structure. On the other hand, it may indicate that the orogenic forces which built the southern Rockies were differently oriented from those which built the northern division and may have originated under different conditions.

DEFICIENCY OF KNOWLEDGE

In figure 1 it is apparent that great gaps interrupt the continuity of examined areas. There are thousands of square miles in the northern Rocky Mountain region which have either not been studied at all geologically or in which geologic observations have been made only in a cursory way. This deficiency of knowledge makes it obvious that generalizations regarding overthrusts and other crustal disturbances in the northern Rocky Mountains should be tentative. Generalizations such as those cited above are valuable, however, as working hypotheses.

OVERTHRUSTING VERSUS UNDERTHRUSTING

Current views regarding overthrusts have in recent years been challenged. Thus Hobbs²² some years ago and more recently Lawson²³ have argued that rocks are underturned and underthrust rather than overturned and overthrust. Mathematical studies of such problems as overthrusting, however logical, are not always convincing, since the results obtained must depend on the validity, comprehensiveness, and accuracy of the assumptions on which the calculations are based. In the Scottish Highlands the imbricated structure appears to bear out Lawson's view that a great wedge of the superficial crust will break up under powerful tangential pressure into smaller blocks that will stand at high angles with regard to the original thrust plane. It shows further, however, that these smaller blocks, when in this position, develop resistances that accumulate in such manner that the blocks may act as a single unit, which, under sufficient tangential pressure, is moved forward with reference to underlying structures.

In most so-called overthrusts the upper block consists of older rocks, more massive and rigid than those that underlie them. It is easier to think of these older rocks, under tangential pressures such as produce these great dislocations, as moving upward and outward toward the surface, where resistance is less, than to suppose that weak, incompetent formations are forced inward and downward into zones of increasing resistance.

With the supposition of underthrusting it is presumed that the greatest effects would be felt near the zone of application of the tangential forces or, in the case of the northern Rockies, along the eastern border of the mountains. If it be presumed further that the zone of application of effective forces might migrate inward—that is, westward—it should be possible to discover relatively younger dislocations in that direction. So far as the facts are known, there seems to be no greater intensity of mountain-building along the eastern border of the Rockies than farther west. Moreover, the Heart Mountain overthrust and possibly the Lewis overthrust, which mark the outer border of the known great overthrusts, are of later date than the Bannock overthrust, and this in turn is probably somewhat later than the Philipsburg faults. Thus it seems that the zone of thrusting has moved progressively eastward rather than westward.

²² W. H. Hobbs: Mechanics of formation of arcuate mountains. *Jour. Geol.*, vol. 22, 1914, p. 206.

²³ A. C. Lawson: Isostatic compensation considered as a cause of thrusting. *Bull. Geol. Soc. America*, vol. 33, 1922, pp. 337-352.

These facts accord better with the idea of overthrusting and a westerly source for the tangential pressures than with the reverse supposition.

In Cadell's experiments, which were conducted with reference to conditions in the Scottish Highlands,²⁴ it was found that the compressed mass tends first to seek relief along a series of greatly inclined thrust-planes which dip toward the side from which the pressure was exerted. After a certain amount of piling up has taken place along these minor thrust-planes, the whole heaped up mass tends to rise and ride forward bodily upon the major thrust-planes. These results correspond with the actual conditions in the Scottish Highlands. The Bannock overthrust, in Idaho, is marked at several places along its course by a fault-zone of heaped-up rock slices inclined westward and consisting of more or less broken rock folds.

Thus far the discussion has assumed that one or the other of the two blocks in an overthrust remains passive. The probabilities are, since gravity plays a predominant part among the forces which produce the tangential pressure, that both blocks are subject to movement, and that the motion of either block with respect to the other is purely relative. This idea has been well expressed by Heim,²⁵ who considers that the curvature of lines of folds affords the best means of determining the direction of this relative movement. He states that the thrust is always directed toward the outside of the arc, in the same manner as an arrow is aimed with a bow.

RESTORATION OF STRUCTURES IN SOUTHEASTERN IDAHO

In figure 2 an attempt has been made to restore the structure of a characteristic portion of the mountains in southeastern Idaho for the purpose of determining the amount of circumferential shortening and of studying the conditions of deformation. The line selected cuts eastward across the northern part of the Aspen Range, in the southeastern part of the Henry quadrangle, and then turns northeastward across the Lanes Creek and Freedom quadrangles to Star Valley a short distance south of the town of Freedom. The methods of restoration and measurement were similar to those employed by R. T. Chamberlin²⁶ for studies in the Appa-

²⁴ B. N. Peach, J. Horne, W. Gunn, C. T. Clough, and L. W. Hinxman: The geological structure of the northwest Highlands of Scotland. *Geol. Survey Great Britain, Mem.*, 1907, p. 475.

²⁵ Albert Heim: *Geologie der Schweiz*, Bd. I, Leipzig, 1921, pp. 647-649.

²⁶ R. T. Chamberlin: The Appalachian folds of central Pennsylvania. *Jour. Geol.*, vol. 18, 1910, pp. 228-251.

———: The building of the Colorado Rockies. *Jour. Geol.*, vol. 27, 1919, pp. 145-164, 225-251.

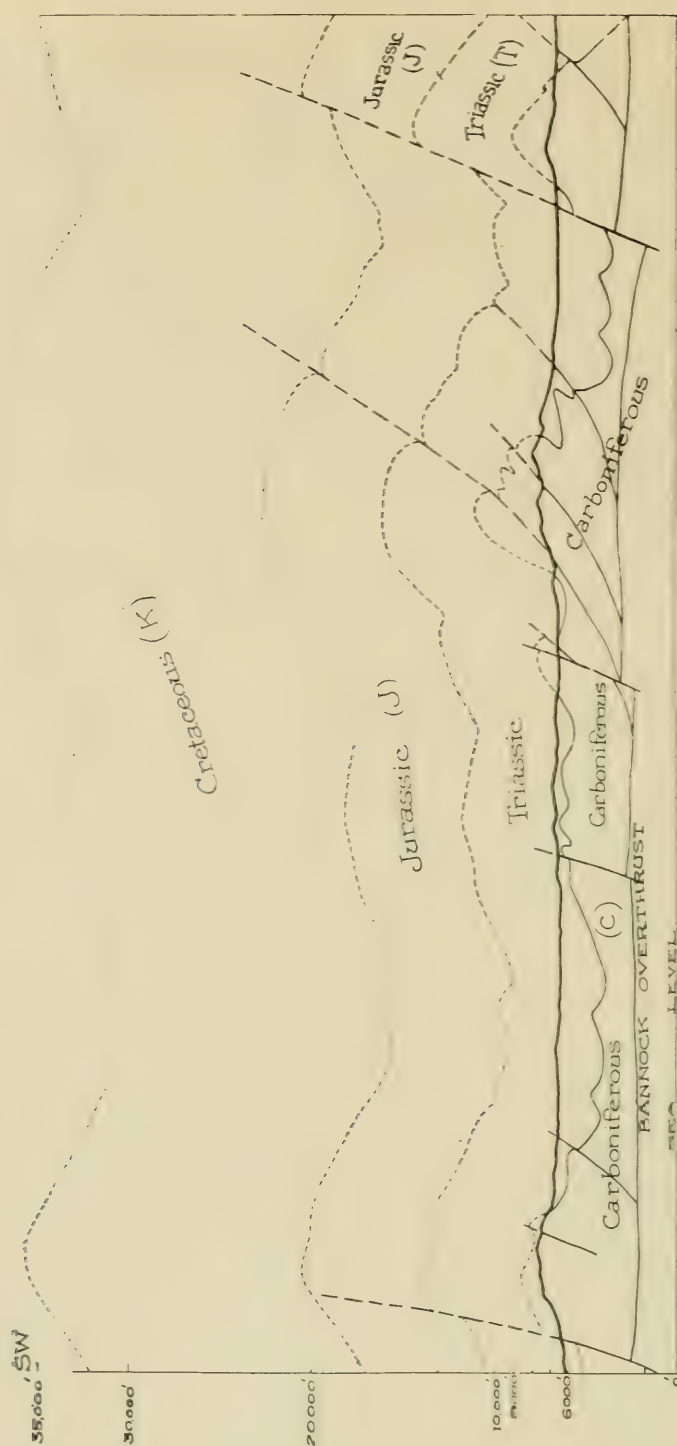


FIGURE 2 A.—Attempted Restoration of Structure in the Rocky Mountains of southeastern Idaho
Southwestern part of the section, including the Aspen Range at the left.

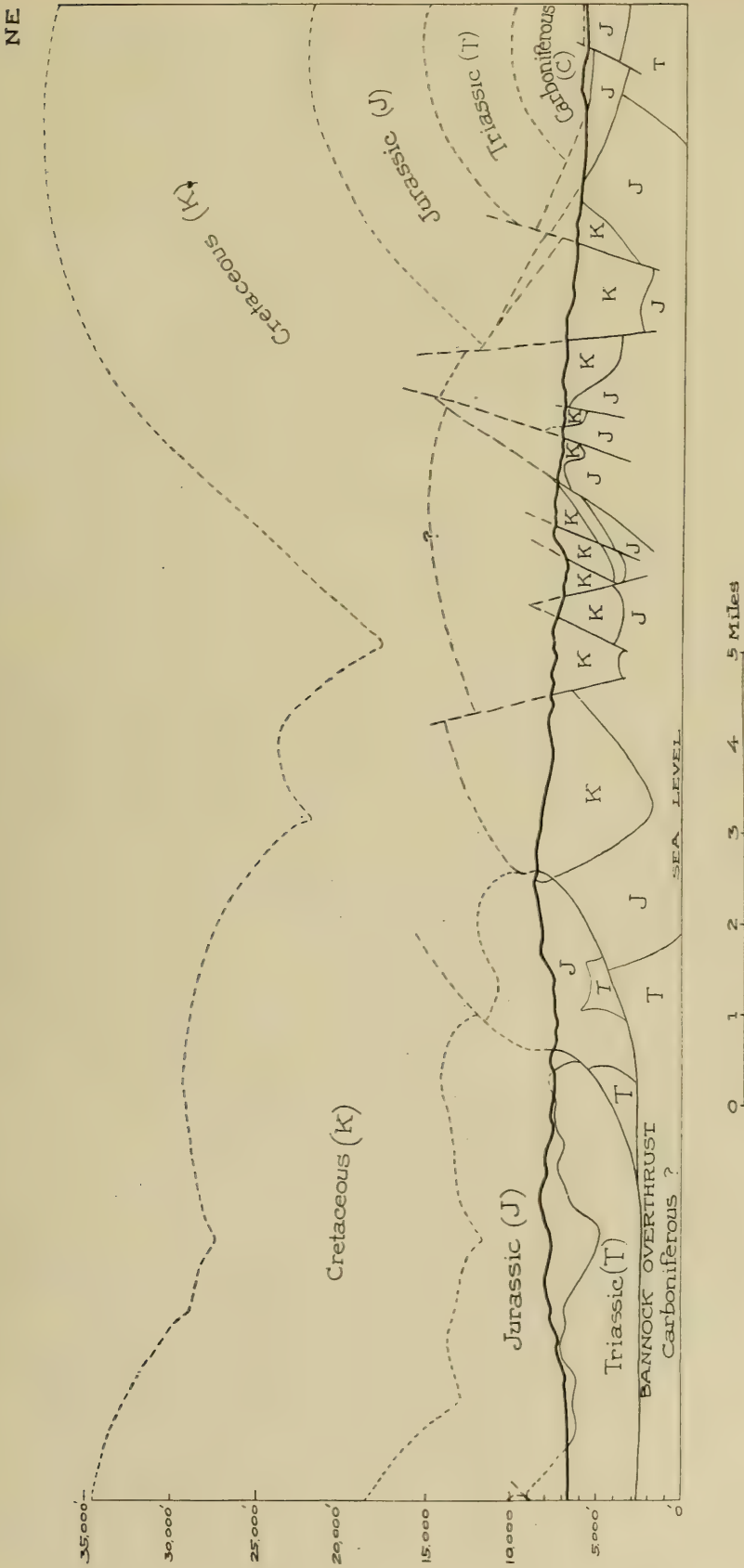


FIGURE 2 B.--Northeastern Continuation of the same Section shown in Figure 2 A, with the Carbon Range at the Right

lachsians of Pennsylvania and in the southern Rockies. All measurements were referred to sealevel, 6,000 feet or more below the present surface, and for the purposes of the restoration it was assumed that the Cretaceous beds present in the northeastern part of the area traversed by the structure section had been deposited over the entire area so traversed—an assumption that seems reasonable. The beds employed for measurement were relatively competent strata that come to the surface at many places.

Considering first the effects of folding without allowance for the Bannock overthrust or for minor faults, the west half of the section, corresponding with the upper part of the illustration, has been shortened 3.9 miles. Similarly the remainder of the section has been shortened 4.5 miles. Considered as a whole, an area 39 miles long has been compressed by folding to 30.6 miles. The actual shortening by this process is 8.4 miles, or 21.5 per cent of the original length. If the minimum horizontal displacement produced by the Bannock overthrust (12 miles) be added to this shortening, the total shortening by both folding and overthrusting, disregarding minor breaks, would be 20.4 miles, or 52.3 per cent of the original length.

The average restored height of the top of the Cretaceous beds above sealevel is 6.7 miles for the western half and 5.7 miles for the remainder of the section; the average height for the entire section is 6.1 miles.

Using the formula $\frac{c}{e} = \frac{h}{d}$, where c represents the amount of linear compression, e the actual length, h the height of the folded mass above the reference plane, and d the depth of the folded mass below the reference plane, we have the following equations:

$$\begin{array}{ccc} \frac{3.9}{14.0} = \frac{6.7}{d}; & \frac{4.5}{16.6} = \frac{5.7}{d}; & \frac{8.4}{30.6} = \frac{6.1}{d} \\ d = 24.1 & d = 21.1 & d = 22.2 \end{array}$$

These results represent respectively the depths below sealevel of the folded mass for the western half, the eastern half, and for the measured area as a whole.

If the minimum displacement produced by the Bannock overthrust be added to the effect of folding, the value for d for the entire area measured would be 9.1 miles instead of 22.2 miles.

Van Hise²⁷ places the maximum depth of the zone of flowage for the strongest rocks at 10,000 to 12,000 meters, equivalent to 6.2 to 7.4 miles.

²⁷ C. R. Van Hise: A treatise on metamorphism. U. S. Geol. Survey Mon. 47, 1904, pp. 189-190.

Willis,²⁸ on the basis of experiments by Adams and Bancroft, thinks that this depth may be as great as 40 miles; but the smaller figure seems to accord better with geologic evidence. The average altitude of the present surface in the western half of the structure section is 1.3 miles, the average for the eastern half is 1.35 miles, and for the whole section 1.33 miles. If these figures are subtracted from the restored heights given above, the results are 5.4 miles for the western half, 4.35 miles for the eastern half, and 4.8 miles for the whole section. These figures, which represent the depth of the present surface below the restored surface, fall well above the depth of the zone of flowage as given by Van Hise and indicate that the visible structures were developed considerably above that zone. This result is in accord with the general absence of regional metamorphism throughout the district represented by the section.

If the average altitude of the present surface be added to the figures obtained above for the depth of folding and compression below sealevel, the average result will be 23.53 miles if only folding is considered, or 10.43 miles if both folding and overthrusting are taken into account. In either case the lower part of the compressed mass should fall within the zone of flowage and the deeper structures should be metamorphosed. On the basis of the figures given above, further erosion, amounting to 0.8 mile or more, will be necessary before the average depth of the metamorphosed portions may be reached.

The principal folding in southeastern Idaho occurred before the overthrust faulting. According to the computations above, the depth affected, when only folding is considered, is greater than the corresponding depth when both folding and overthrusting are taken into account. These data suggest that in the earlier stages of compression the earth's crust was more deeply affected than at later stages. In other words, the zone of compression as it became more intense migrated outward toward the surface.

It has been stated that some of the folds mapped in southeastern Idaho exceed 50 miles in length and 3 miles in width. Seen in the field, each of these structures appears to be relatively large and independent, though many smaller folds are present. The restoration, figure 2, shows that the large folds in turn are members of still larger structures, and that the region traversed by the structure section contains the greater part of two such folds, an anticline and a syncline, each of which is approximately 15 miles wide. The size of these larger structures, which may be termed major folds, affords a means of comparison of the intensity of

²⁸ Bailey Willis: Discoidal structure in the lithosphere. *Bull. Geol. Soc. America*, vol. 31, 1920, pp. 247-302.

compression in different regions where mountain-building has occurred. Thus in the island of Anglesea, whose highly complex geology has been studied in great detail by Greenly,²⁹ the accessible part of the Holyhead recumbent fold is said to have a real horizontal amplitude of about 60 miles. Great thrust-faults are also present. It is apparent that in Anglesea the compressive forces were more intense than in southeastern Idaho.

ISOSTATIC FEATURES

In the Alps, as described by Heim,³⁰ the gravity defect is at a maximum under the line where the "decke" folds of relatively lighter rocks were originally piled highest. It is normal at the south foot of the Schwarzwald to the north and in excess at the top of the Schwarzwald. Similarly, near Locarno, at the south, there is another area where gravity is in excess. This is the belt where the roots of the folds that now form the "decke" are supposed to lie and where basic eruptives are now heaped up. The surface of normal gravity lies unsymmetrically beneath the Alps, its gentler and longer slope passing upward toward the north. The folded complex of the Alps is thus believed to float with its deeper parts concealed in the earth's crust, much as an iceberg floats in the sea. This attitude is produced by sinking, in consequence of the overload due to the compression of the crustal mass. So it happens that the Alps are not 5 to 10 times higher.

A different condition seems to obtain in southeastern Idaho. On the map of gravity anomalies, published a few years ago in Gilbert's paper,³¹ southeastern Idaho is shown to possess an excess of gravity, while central and northern Idaho and adjacent parts of Montana are deficient. These last named regions are areas of batholithic intrusion. Under the isostatic theory, batholithic intrusions might normally be expected to occur in regions adjacent to areas of intense folding and overthrusting. This is apparently the case in the Alps. Since folded sedimentary rocks are relatively lighter and intrusives supposedly heavier, the plus anomalies, representing excess of gravity, should, under the hypothesis, lie in the batholithic areas and the minus anomalies in the sedimentary areas. This again is apparently the case in the Alps, but the reverse actually happens in southeastern Idaho. The Snake River lava plains lie in the area of excess gravity, and the weight of the basalts that underlie these

²⁹ Edward Greenly: The geology of Anglesea. Geol. Survey Great Britain, Mem., 1919, p. 181.

³⁰ Albert Heim: Geologie der Schweiz, Bd. II, Erster hälfte, Leipzig, 1921, pp. 52-56.

³¹ G. K. Gilbert: Interpretation of anomalies of gravity. U. S. Geol. Survey Prof. Paper 85, 1914, pp. 29-37.

plains may have a bearing on the problem. On the other hand, the Columbia River basalts lie in an area in which there is a gravity defect. Extensive sedimentary areas occur in Colorado, Utah, Wyoming, Montana, and farther eastward. These have plus anomalies which seem to indicate that much of the mountain-built area is not fully compensated, and that the batholiths of central Idaho and Montana may not have a close isostatic relationship to the folded rocks of the northern Rockies.

In the symposium on isostasy at Amherst last year Reid³² called attention to the fact that isostatic sinking tends to offset the effects of folding, thereby militating against the elevation of mountains to great heights by compression. He raised the question whether folding can actually produce high mountains. The present study affords a means of testing this question.

The Snowdrift peneplain, which is the highest recognized erosion surface in southeastern Idaho, represents the surface to which the mountains were there reduced by erosion after the Laramide folding and after the sinking of the folded mass under isostatic conditions. This peneplain, which now stands 9,000 feet, or 1.7 miles, above sealevel, probably affords a maximum measure of the amount of subsequent uplift which the folded area has experienced in being elevated to its present position. If this is subtracted from the theoretical elevation, 6.1 miles, suggested by the restoration of the upper beds of the Cretaceous, figure 2, there still remains a difference amounting to 4.4 miles. How much of this difference to allow for the erosion that prevented the mountains from attaining the full height to which the folding might otherwise have raised them it is impossible to say from present data. If it be assumed that this erosion consumed half or two-thirds of the folded mass, the mountains might have reached elevations ranging from 1.5 to 2.2 miles. It appears, therefore, that folding of the strata, with due allowance for isostatic sinking, may produce mountains comparable in height to those of today. This is without regard for any allowance that might be made for changes in density of material within the mountain mass induced by unloading through erosion, which would tend to further increase the height of the mountains. The later uplifts, which most of the higher ranges have experienced, represent separate mountain-building activities of perhaps another sort, but it is not necessary to infer from their presence that high mountains may not be formed by folding alone.

³² H. F. Reid: Isostasy and earth movements. *Bull. Geol. Soc. America*, vol. 33, 1922, pp. 323-324.

HYPOTHESES OF MOUNTAIN-BUILDING

Kober's hypothesis, which has been ably outlined by Dr. Longwell in a preceding paper, is presented in a very interesting and plausible way. The general arrangement of western and eastern mountain chains with intervening plateaus and ranges has a superficial agreement with his plan. The Rocky Mountains in Idaho and northward show eastward overturning and overthrusting, which accords with Kober's hypothesis; but the case for the Coast ranges, which by hypothesis should be overturned westward, is not so clear. The structure sections studied by the writer, though showing intense folding and faulting, do not indicate a predominant direction of overturning or overthrusting. Moreover, the distribution of igneous intrusives in the Coast ranges is not very favorable to the hypothesis. It may be questioned, too, how far the interior plateau and ranges accord with the conditions of his plan.

Professor Hobbs, in the book²² to which he referred in his paper, postulates a two-sided symmetry for the Pacific mountain region, due to eastward underthrusting on the west side, caused by the subsidence of the Pacific Ocean, and to westward underthrusting on the east side, caused by the subsidence of the "Laramide Ocean." The subsequent settling of the Great Basin and its extension to the north caused further underthrusting on the east and west sides of this area, represented respectively by the Wasatch and Sierra Nevada escarpments, and produced bilateral symmetry for the Rocky Mountain group on the east and for the Sierra Nevada-Coast Range group on the west. Objections to this hypothesis, so far as the Coast ranges are concerned, have been stated in the preceding paragraph. The view that the Wasatch and Sierra Nevada Mountains are bounded by thrust faults inclined respectively east and west requires further demonstration. The writer's views regarding underthrusting in the eastern ranges of the Rocky Mountains have already been stated (see page 272). All geologists will agree that the sea extended in Cretaceous times along the eastern front of the Rocky Mountains and even covered areas that are now included in the mountainous belt. This sea, however, was in no sense an ocean, as the term is now understood. It was rather an epicontinental sea of relatively shallow water. This is clearly indicated by the nature of the deposits.

Professor Willis's discoidal hypothesis, which has been set forth in an earlier paper in this symposium, though based on careful computations and plausibly presented, is dependent on the validity of its fundamental

²² W. H. Hobbs: *Earth evolution and its facial expression*. The Macmillan Co., New York, 1921, pp. 119-134.

assumptions. These are extrapolations on a large scale from the results of experiments which may not be directly applicable to the earth. Although the preliminary test of this hypothesis with the Sierra Nevada Mountains and Coast ranges appears to him to have been successful, it is thought that the conditions in the northern Rocky Mountains, where the great overthrusts have large horizontal components, will prove less favorable to it, and that it may not be widely applicable.

Thom's hypothesis postulates that compressive movements are active in the deeper and more rigid parts of the shell beneath the overlying sediments, and that the deformation of the latter is directed or controlled in part by the deformation of the former. This view appears sound. His statement, however, that the intense compression in the outer portions of the crust was dissipated by overthrusts, but that the deeper part continued to be deformed, suggests that the structures which he describes are younger than the overthrusts. It has been shown on page 272 that the development of overthrusts was probably progressive, both in space and time, and that the easterly overthrusts were the latest formed. It was also suggested, on the basis of the apparent depth of the folds, that the zone of compression, as it became more intense, may have migrated outward toward the surface. If these suggestions are well founded, it may be that the structures described by Thom, both the deep-seated and the more superficial, were formed before the overthrusts occurred, and that they may have played an important part in localizing the overthrusts.

CAUSES OF MOUNTAIN-BUILDING

The primary cause of mountain-building is unknown. However, the abundant evidence of compression found in most mountain regions implies a shrinkage of the earth to a smaller volume. Numerous agencies have been recognized as contributory to this result, among which are cooling, crystallization, progressive condensation under gravitative influences, molecular and subatomic changes, redistribution of internal heat, and perhaps other causes. Gravitative readjustments take place periodically, as a result of accumulating stresses, rather than continuously. The origin of igneous magmas is closely interwoven with these readjustments, and the movements or intrusions of these magmas play an important part in the distribution of temperatures and in the application or localization of stresses within the earth's crust. The net result of these various agencies, so far as mountain-building is concerned, is to produce the compressive stresses that in turn produce the folding and overthrusting.

Two phases of this compressive activity are illustrated in southeastern Idaho. The earlier phase was that in which the folded and overthrust structures, which form so conspicuous a feature of the mountains, were developed. The compression at this time was localized by a deeply loaded geosyncline. The mountains formed are believed to have been comparable in height to those of today or even higher. They were reduced, however, to a peneplain, or were at least greatly worn down. The second phase was inaugurated by a renewal of the periodic contractional disturbances of the earth. This time the effects were not so definitely localized as before, probably because no accumulation of sediments comparable to those of the former geosyncline had taken place and the rigid crust was, therefore, not weighted down as before. The result was a broad uplift, with only gentle foldings or warpings.

TENSIONAL FEATURES IN MOUNTAIN STRUCTURE

Kober in his book, about which this symposium centers, takes exception to current views regarding normal faults and undertakes to show that these are compressional features. The Rhine Valley graben, which has become a classic example of normal faulting, he regards as a summit break in a great anticline. He finds overthrust faulting in the vicinity of the graben and an actual overriding of the horsts upon the graben. Kober ascribes the horst and graben structure, which dominates in Germany, to the irregular elevation of an old peneplained mountain chain, which, by renewed undulation due to contraction of the earth's crust, has been broken into blocks. The height of the blocks is not equal and not very great; their borders are broken and overthrust; the higher uprising blocks tend to overspring the deeper lying basin and trough portions. Kober points out that these structures are very young, that the movements are still in progress, and that the superficial shoving together of the horsts may in time go so far as to lead to the overriding of one by another. Thus the intervening graben break might become an overthrust.

No extended discussion of this view may be undertaken here, but it is believed that the studies thus far made in southeastern Idaho have brought out definite evidence unfavorable to it. The Meadow Creek graben, which has been described elsewhere,³⁴ is bounded by horsts that contain folded structures, but no tendency of either horst to override the graben has been recognized. Both horsts and the intervening graben have been cut by transverse faults in such manner that in the area between

³⁴ G. R. Mansfield: Types of Rocky Mountain structure in southeastern Idaho. *Jour. Geol.*, vol. 29, 1921, pp. 460-465.

these faults the distance between the horsts has been increased. Had these faults and the boundary faults of the horsts been overthrusts, this distance should have been diminished rather than increased.

In general, there seems no good reason for abandoning the idea that tension faults do exist and that they may play an important part in mountain structure. The current view that tensional faulting serves as a method of relief for overstrained or overcompressed structures is believed to be well founded.

SUMMARY

On the basis of detailed studies in southeastern Idaho and more cursory observations in Montana and elsewhere, some of the broader structural features of the northern Rocky Mountains are discussed.

A review of the great thrust-faults as described in the literature shows that they vary in length from a few miles to nearly 300 miles, and in amount of dislocation from 2 or 3 miles to nearly 40 miles. They vary also in age, the later ones lying nearer the eastern front of the mountains. Thom regards these faults as parts of a continuous major fracture, along which the great overthrust sheet impinged upon older east-west uplifts and was disrupted by them. Kober considers the eastern ranges of the Rocky Mountains as border chains of a geosyncline thrust forward upon a foreland. These views are briefly discussed as working hypotheses.

The question of underthrusting as opposed to overthrusting is outlined and the conclusion reached that the available geologic evidence favors overthrusting, though it is recognized that the direction of movement may be relative and that both upper and lower blocks may be actually involved in the movement.

On the basis of an attempted restoration of structure in southeastern Idaho the following conclusions were reached:

Crustal shortening by folding alone amounted to 21 per cent, or, considering both folding and overthrusting, to 52 per cent of the original length of the area studied.

The depth affected by folding alone was about 22 miles, but if overthrusting and folding are considered together, this depth is reduced to 9 miles. The lower portions of the folded structures should therefore be metamorphosed, but further erosion of at least 0.8 mile will be necessary to expose the metamorphosed portions.

Since the overthrusting was a relatively late feature of the deformation, the earth's crust was more deeply affected during the early stages and the more intensive effects were shallower.

The larger folds actually seen are parts of still larger (major) folds 15 miles or more wide.

Consideration of isostatic conditions in the northern Rockies shows a less favorable relationship between the distribution of gravity anomalies and mountain structures there than in the Alps. The northern Rockies are apparently not fully compensated. The relationship of the Snowdrift peneplain to the restored structures seems to indicate that isostatic sinking does not fully offset the effects of folding and that high mountains may be formed by folding alone.

Several hypotheses of mountain-building are discussed in their bearing on the northern Rockies. It is concluded that compressive stresses, originating in gravitative readjustments within the earth and influenced to a greater or less degree by magmatic movements, were localized by the heavily loaded geosyncline, which became folded and overthrust, producing high mountains that were subsequently peneplained. Later compressive stresses, originating in a similar manner but not localized by sedimentary accumulations, caused broad upwarps and gentle folds, which gave the mountains their present elevations.

Kober's view, that horsts and gräben are due to compressive agencies, is not supported by geologic evidence in southeastern Idaho. Such structures are still regarded as of tensional origin and as affording means of relief from the overcompression incident to mountain-building.

BUILDING OF THE SOUTHERN ROCKY MOUNTAINS ¹

BY WILLIS T. LEE

WITH

NOTES ON ISOSTASY

BY C. E. VAN ORSTRAND

AND

ELASTIC YIELDING OF THE EARTH'S CRUST UNDER A LOAD OF
SEDIMENTARY DEPOSITS

BY WALTER D. LAMBERT

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INTRODUCTION

This paper concerns the Southern Rocky Mountains, lying chiefly in Colorado. Certain recorded observations relative to them are recalled and possible causes of their rise discussed. It is shown that the theory of lateral compression, frequently advanced as the cause of mountain-building and recently applied by R. T. Chamberlin to the Colorado Rockies,² is not in harmony with many of the observed facts, and the

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² R. T. Chamberlin: The building of the Colorado Rockies, Jour. Geol., vol. xxvii, 1919, pp. 145-164, 225-251.

question is raised, if changes in temperature, density, mineral constitution, etcetera, can explain such elevations and depressions as are known to have occurred. The building of the Southern Rockies might be discussed from the standpoint of probability and possibility, but when requested to speak on this subject it seemed to me that the only way in which I could contribute to the much-discussed question of mountain-building would be to outline a definite problem and to seek for such quantitative data as might help in solving it.

RECITAL OF CERTAIN OUTSTANDING FACTS

In this brief paper minor details must be omitted, as must also many references to publications on which statements are based. Some of the large outstanding facts which I shall make use of, and which have not been seriously challenged, are as follows: In late Carboniferous time mountains which have been called the Ancestral Rockies, comparable in size to the present Rocky Mountains, occupied the site of the Southern Rockies and sediments were shed from them in all directions. East of these mountains the sediments accumulated chiefly as upland and brackish water deposits to form the gypsiferous red beds of the West. West of the mountains the material found its way toward the Pacific through shallow seas in Permian and Lower Triassic time and accumulated as lowland deposits in late Triassic time. Through the succeeding ages the Ancestral Rockies were eroded to such an extent that at the

LEGEND FOR FIGURE I

A, curvature of the earth's surface along the 39th parallel from the high Sierra in California eastward for 1,000 miles, showing the relative position of the Great Basin, the high plateaus, the Southern Rocky Mountains, and the Great Plains. At this latitude the earth's radius is 3,968.6 miles. The chord of the 1,000-mile arc is about 997 miles and the maximum distance between chord and arc is nearly 34 miles. The part of the arc between Wasatch Mountains and central Kansas, about 700 miles, represents the Interior Cretaceous Basin. The maximum distance between this arc and its chord is about 12 miles. The sedimentary rocks which filled this "basin" are less than 2 miles thick; therefore they form an onion-skin shell laid down on a surface which was always convex, although slightly less so than the normal convexity of the earth's surface.

The illustrative profiles B-G, representing the same arc in successive ages, are drawn for convenience with straight line rather than arc representing sealevel, and with exaggerated vertical scale. B represents early Triassic time, when the Ancestral Rockies were high and the sea occupied areas west of them; C=late Triassic time, when the mountains were eroded, the sea filled, and products of erosion accumulating above sealevel to form the non-marine Triassic; D=early Jurassic time, after the rise of the Nevada continent and the reduction of the Ancestral Rockies to a peneplained condition; E=the beginning of the Upper Cretaceous epoch, when the Ancestral Rockies were base-leveled; F=the close of the Cretaceous period, after the Cretaceous Basin was filled with sedimentary rock; G=the present time, showing the Great Basin lower than the plateaus whose material was derived from it and the still higher Southern Rockies standing in the middle of the area formerly covered by the Cretaceous Sea.

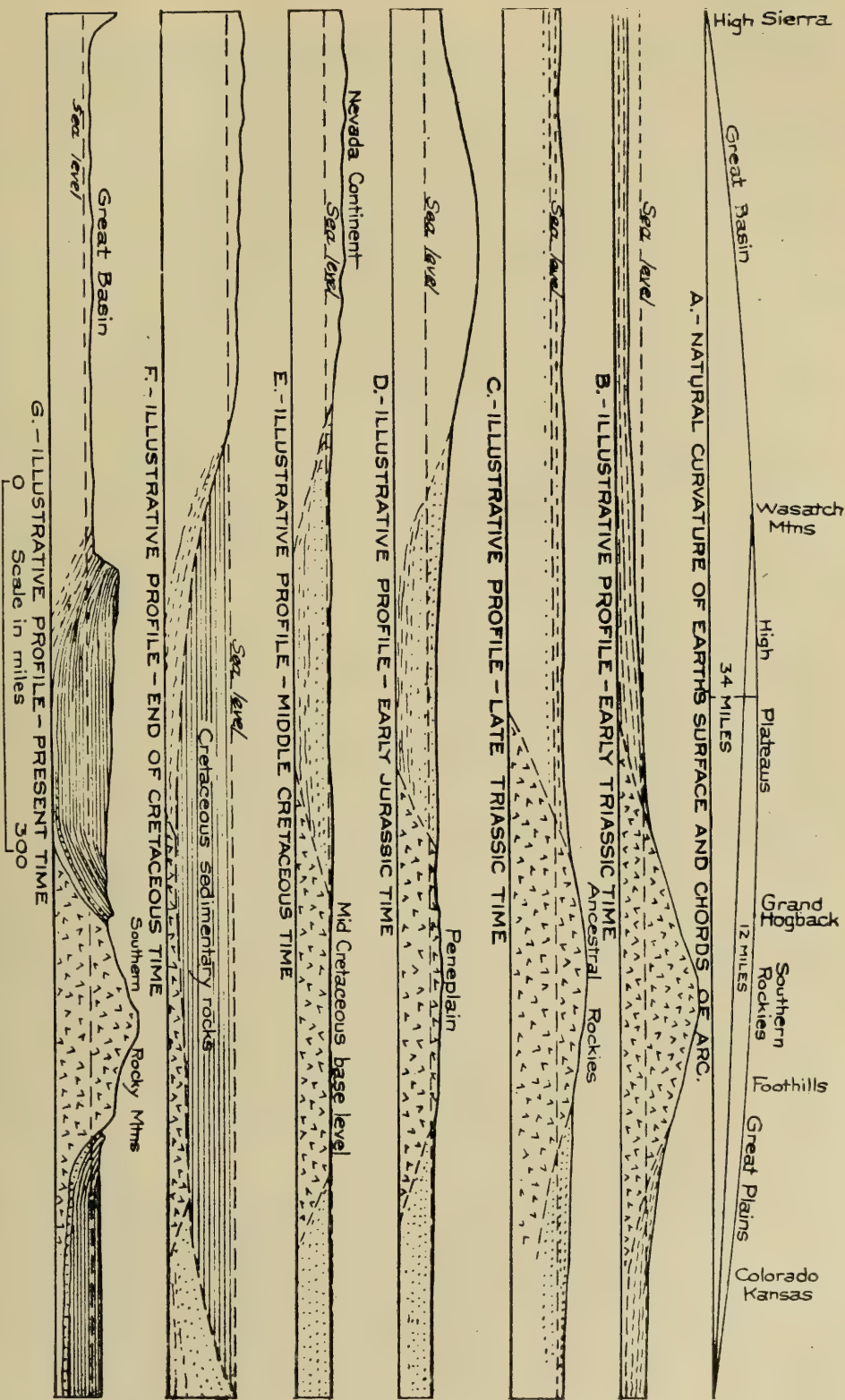


FIGURE 1.—Relation of the Interior Cretaceous Basin to the Ancestral Rocky Mountains, the Nevada Continent, and the present Rockies

opening of the Upper Cretaceous epoch they were worn down to baselevel. In the meantime a broad highland of continental proportion seems to have arisen in the region of the present Great Basin, cutting off connection with the Pacific, and detrital matter from this new highland spread eastward over the space between this newly formed continent and the last survivals of the vanishing Ancestral Rockies.

As the submergence of the baseleveled Ancestral Rockies is an important consideration in this discussion, I pause here to note that some still cling to the belief of the earlier workers in this region, that certain "islands" persisted in the Southern Rocky Mountain Province throughout Cretaceous time. But the announcement years ago that no such "islands" could be found, and that there are good reasons for believing that the Upper Cretaceous formations once extended uninterruptedly over the site of the Southern Rockies, has not been challenged. Until this concept is shown to be untenable, I may reasonably assume that the Rocky Mountain geosyncline which formed in western North America in Cretaceous time included the site of the baseleveled Ancestral Rockies.

The sea entered the geosyncline and for a long time received and distributed the detrital matter from the newly formed uplands to the west. It would seem from some writings that the trough is supposed to have formed rapidly, and that the interior sea was deep and open throughout Upper Cretaceous time. Opposed to this is the radically different conception that the geosyncline formed slowly; that the waters throughout the epoch were so shallow that fine material was distributed somewhat uniformly over the bottom; that the filling practically kept pace with the sinking of the bottom, and that several times during the Upper Cretaceous epoch sand and silt entering from the west built low marginal plains over large areas from which the sea water was temporarily excluded. The slow subsidence of the trough, coupled, perhaps, with a rise of sealevel, and the conflict between sea and sediments continued until several thousands of feet of material, mostly sand and silt, had accumulated.

Then, at the close of the Cretaceous period, the crustal movement was reversed. The deeply buried base of the Ancestral Rockies was raised and highlands reappeared where the sea had been. Here again a common conception seems to be that a radical change occurred and a rapid rise of land took place to mountains of such proportion as now exist. Opposed to this is the conception that the first uplift—that is, the one which closed the Cretaceous period—was relatively mild. The significant fact, however, is the reversal in the direction of movement. The rate and extent of uplift are of minor consequence.

Only a few outstanding facts relative to the later history of the Rocky Mountains need be mentioned in this connection. First, it is beyond dispute that since the relatively small uplift at the end of the Cretaceous period the Rocky Mountain region has never been submerged, although parts of the continent at a distance from these mountains subsided beneath sealevel in Tertiary time; second, there were periodic uplifts during the Tertiary and Quaternary periods, accompanied by warping of the surface and extrusion of igneous rock. Much of the evidence of the earliest Tertiary movements has been destroyed by erosion, but the later uplifts and cycles of erosion are recorded in the old peneplains, one of which is now found in northern Colorado at an altitude of about 12,000 feet, and another at 10,000 feet. Doubtless remnants of other persistent plains will be found. These plains are raised somewhat more in some places than in others and show some warping, but on the whole they suggest vertical uplift. In brief the mountains have been periodically rising from the close of the Cretaceous period to the present time.

Some of the minor features are important in indicating the manner in which this rise occurred. Throughout the mountain region overthrust faults are rare and normal faults are numerous. With few exceptions, displacements along the foothills may reasonably be attributed to drag in the rise of the mountains, and to such secondary action as sag following a period of uplift, and to local lateral crowding at the edges of the sagging mass. Lest I be misinterpreted, let me reiterate that I am speaking of the Southern Rockies alone and not of parts of the Wasatch Mountains and other places still farther to the west and north, where great overthrusts have occurred.

There are few so-called rock folds in the Southern Rockies of such character and magnitude as to enter seriously into the problem of mountain-building. These are the hogbacks, formed by the upturning of the sedimentary formations on all sides of the mountains and the large down-warped or less uplifted areas, as one chooses to think of them, in North, Middle, and South parks, and other less conspicuous features, commonly classed as folds, such as the *en echelon* folds of the foothill region and the less conspicuous undulations of the sedimentary rocks of the plains, which, in my opinion, should be expressed as warping rather than as folding under lateral compression. It is a common custom to connect the upturned beds of the foothills with the isolated remnants of the same beds high in the mountains, in such a manner as to make it appear that they once extended in a continuous undulating but unbroken surface over the range. This practice may be justifiable for certain purposes.

but such illustrations should not be interpreted as proof of lateral compression or foreshortening of the crust. The upturning of the foothill formations is as readily explained by drag during vertical uplift as by wrinkling under lateral compression, and the isolated remnants high in the mountains are more readily explained by vertical uplift than otherwise.

In studying the foothill region it becomes strikingly obvious that, with few exceptions, the sedimentary formations lie nearly horizontal or are only gently warped; but at the foot of the mountains they are either sharply upturned or broken off at nearly vertical fault planes. There is conspicuous absence of minor lateral folds parallel to the main axis. It is difficult to understand, if the mountains are due to lateral compression, why secondary folds are not more numerous. On the other hand, the abrupt upturning of the sedimentary rocks in the foothills and the breaking along vertical planes seem normal in case the upturning is due to drag on the flanks of the rising mass.

Again allow me to guard these statements with the assurance that I am not including areas beyond the limits of the Southern Rocky Mountain Province, for in areas beyond this province lateral compression, to some extent at least, is evidenced by overthrust faults and by folds parallel to the axis of uplift. Nor am I thinking of the mountain mass as a rigid unit. In my opinion, the anticlines and domes in the relatively low-lying oil region of southern Wyoming immediately north of the Southern Rockies gives a picture of the more highly lifted mountainous area as it would have appeared had erosion not removed the sediments from the top. Here the strata are thrown into a series of domes, anticlines and synclines, of different sizes and shapes, which have about as much symmetry as the similar heights and hollows would have on a mass of yeast-rising dough. I am inclined to think that if this nonmountainous area immediately north of the high mountains had been pushed up vertically several thousand feet higher than it is, it would now, after erosion, present about the same aspect that the mountains have.

Perhaps one more consideration in this connection may be excusable. It is a matter of observation that some of the few minor folds which lie parallel to the foothill ridges are asymmetric, with the steeper side toward the mountains. On the supposition that the mountain mass was squeezed up by lateral pressure, these folds may be regarded as incipient overthrusts tending to ride up onto the flanks of the range. On the other hand, they may be explained as readily by local sag or settling of parts of the mountain mass following an uplift. Such settling would

tend to spread the mountain at its base, raise the surface just beyond the base, and at the same time force the spreading mass under the raised part on the mountainward side, simulating the familiar phenomena of overthrust. Such sagging may or may not be adequate to explain large lateral thrusts, but I know of no folds of post-Cretaceous age in the Southern Rockies which could not be as readily explained in this way as by lateral thrust.

In brief, I can see no essential difference, except size, between the Southern Rockies, the Black Hills, and certain still smaller groups of mountains which are subcircular in outline and which may be compared to raised blisters rather than to wrinkles on the face of the earth.

THE SOUTHERN ROCKIES AS A QUANTITATIVE TEST

If it be conceded that the Southern Rockies were formed by vertical uplift rather than by lateral pressure, it remains to find adequate causes of the uplift. The processes resulting from the existence and maintenance of isostatic equilibrium, discussed at the Amherst Meeting of this Society a year ago and in recent papers by William Bowie and others, considered qualitatively, seem to offer an explanation of the rise of the mountains, but a quantitative test is needed. It seems to me that the Southern Rockies offer as good an opportunity for making this test as is likely to be found.

Considering the great quantity of detrital material derived from the Ancestral Rockies, it seems reasonable to assume that the ancient range was comparable to the present mountains. It was formed at the close of the Pennsylvanian epoch, let us say thirty million years ago. It was eroded through succeeding ages and became baseleveled about the middle of the Cretaceous period. In the meantime, presumably at the close of the Triassic period, the western landmass, which may be called the Nevada continent, was raised, and sediments from it spread eastward in Jurassic and Lower Cretaceous time. At the beginning of the Upper Cretaceous epoch the baseleveled site of the Ancestral Rockies began to settle beneath sealevel and was covered by the water of the Interior Cretaceous sea. From this time to the end of the Cretaceous period the Nevada continent supplied rock debris which lodged in the Cretaceous basin, to thicknesses in the vicinity of the present mountains approximating 10,000 feet. At the end of the Cretaceous period a reversal of movement set in, and from that time to the present the movement has been haltingly upward.

EXPLANATION OF THE MOVEMENT

Thus far the geologist may feel secure in offering the final word; but for explanation of the movements he must seek advice. From the numerous unsolved problems, I venture to select three and inquire if geophysicists can offer solutions.

First. Was the time—let us say 20,000,000 years—between the close of the Pennsylvanian epoch and the opening of the Upper Cretaceous epoch, during which the Ancestral Rockies were reduced to baselevel, sufficient for the establishment of perfect adjustment of physical conditions? Had the movement of isogeotherms ceased? Had such recrystallization or metamorphism as was appropriate for the changed temperature and pressure been accomplished? Had perfect balance between those forces which make for rise and fall of land surface been attained?

Second. Observation establishes the fact that downward movement ceased at the close of the Cretaceous period and the deeply buried rocks of the mountains began to rise. Are changes in temperature, mineral constitution, specific gravity, etcetera, within the rocks of the mountain region competent to halt and reverse such a movement, or must some external force be called in?

Third. Observations establish the fact that the rise of the Southern Rocky Mountains inaugurated at the close of the Cretaceous period continued until not only was the old surface, which had been depressed 10,000 feet, restored to its former position, but was raised in some places to more than 15,000 feet above sealevel. This rise took place periodically during the time, perhaps 5,000,000 years, since the close of the Cretaceous period. Are the changes in the physical character of the rocks of the mountain region competent to produce a rise of 25,000 feet in post-Cretaceous time, let us say 5,000,000 years, or must we look to some other cause for an adequate explanation?

The rise of the Rocky Mountains, because of superficial transfer of material or lateral thrust of the crust of the earth, seems to be barred from consideration by the observed structure. Their rise because of injection of large masses of matter or transfer of deep-seated material from a distance seems barred by the isostatic equilibrium of the crust beneath the mountains, for pendulum observations show no excess of mass. Highlands and lowlands alike are found to be in essential isostatic balance—a condition which could scarcely exist if the mountains had been forced up by injection of material. In other words, the highlands are highlands because the material of the mountain block is less dense than the material of neighboring blocks. The mountains rise

above sealevel for the same reason that a cake of ice rises above the level of water in which it floats.

It remains then to inquire if masses of rock may undergo sufficient change in volume from age to age to account for the demonstrated rise and fall of the surface in mountainous regions. This inquiry involves a great number of questions which can not be answered, some for which the geologist has a qualitative answer, and a few for which a quantitative answer may be found.

It is well known that rock increases in volume with increase in temperature and diminishes with decreasing temperature. The rate of heat transfer through rock is shown by Van Orstrand in the appended notes to be so slow that its effects may lag far behind those of erosion

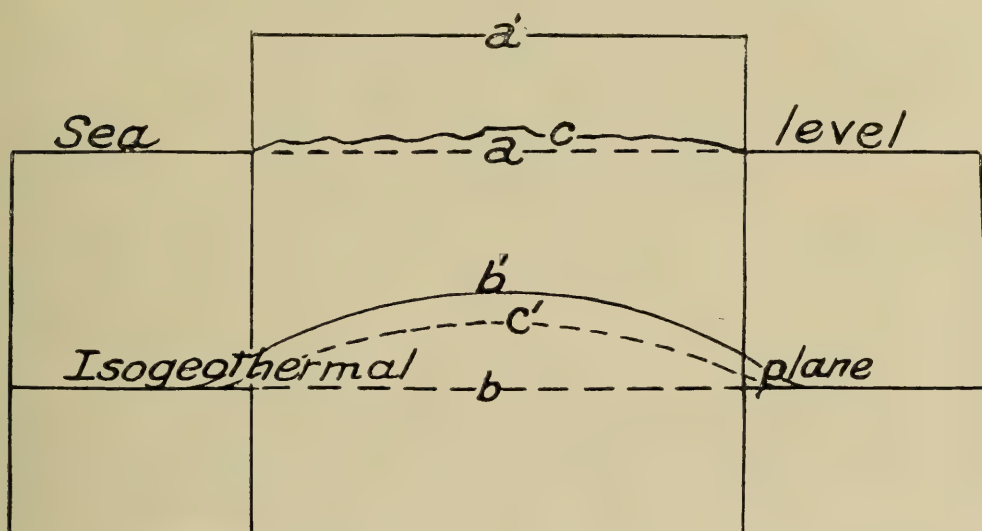


FIGURE 2.—Diagram illustrating Deformation of isogeothermal Planes and their Relation to Erosion

and deposition. As the Ancestral Rockies were lifted from position *a* to *a'* of figure 2, the isogeothermal planes beneath them were bent upward from position *b* to *b'*. As material was eroded from the top *a'* the earth block continued to rise and maintain isostatic balance, carrying the isogeothermal planes still higher. The lifting of the isogeotherms was opposed by cooling, which tends to lower them. But their movement seems to have been so slow that the mountains were eroded away to *c* by the time the isogeotherm *b'* was lowered to some such position as *c'*. As the earth block continues to shrink, due to continued lowering of isogeotherms, the surface is drawn below sealevel, allowing sediments to accumulate on it. This sinking of the Rocky Mountain region began about the middle of the Cretaceous period. A picture of the later action is given in figure 3.

The surface *a* is depressed with added load to *a'*, and the isogeothermal plane *b* sinks toward *b'*. The isogeotherm tends to rise, but its upward movement is slow because of low conductivity of rock. When expansion under rising temperature reduces the density to that of the neighboring rocks, subsidence ceases, but the isogeotherm *b'* has not yet returned to position *b*. As rise of temperature proceeds, the density of the material in the column decreases because of expansion, and the surface rises to position *c*. This raised part is eroded, and the column, now lighter than

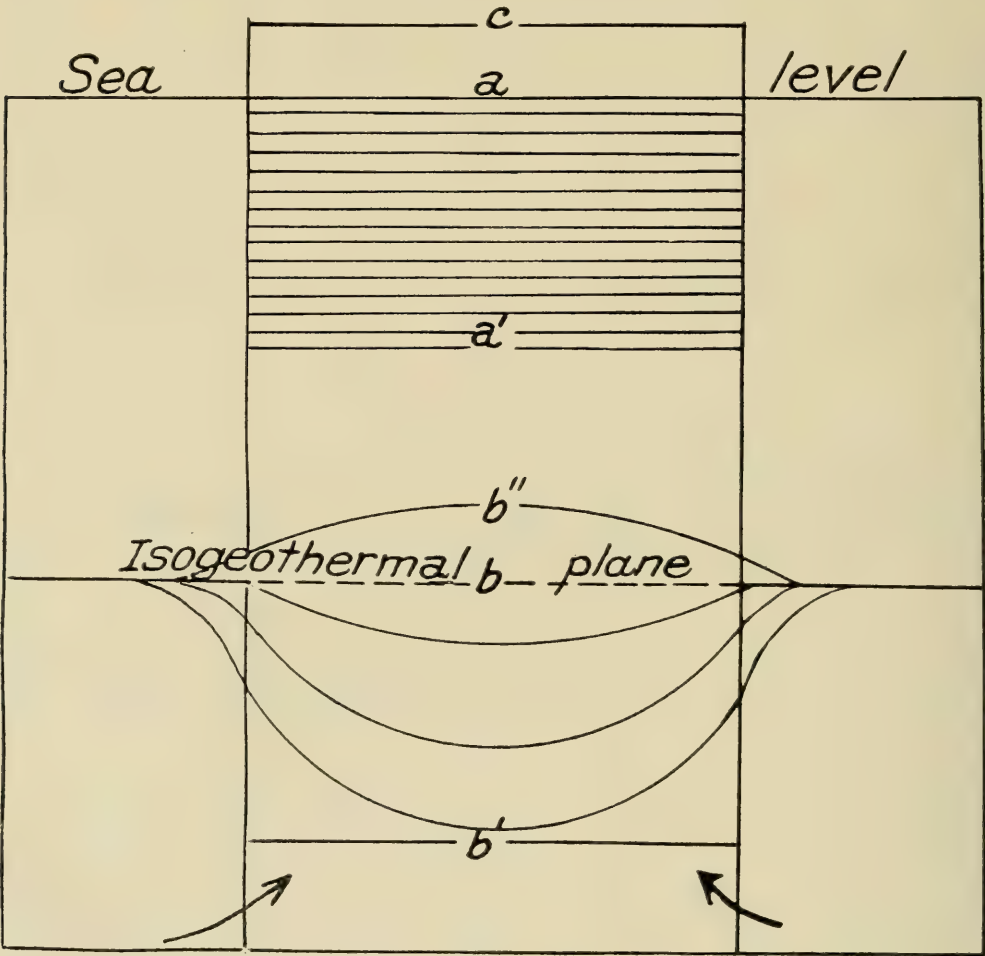


FIGURE 3.—Relation of Isogeotherms to a sinking Earth Block

the surrounding material because of decreased density and also because of the removal of surface material by erosion, tends to rise or “float” upward, as explained below, while material from below is forced into the abandoned space. As the column rises, the isogeothermal surface *b* is carried up to *b''*, a position higher than is normal. The tendency of the isogeotherm is now downward, but the lag due to low conductivity allows

much rise of the column before the increasing density due to cooling halts the downward movement.

In order to visualize the results of the processes discussed, we may compare the column of rock beneath the mountains to a cake of ice bc floating in water, the surface of which is represented by aa' of figure 4. As the ice melts at the top under heat applied at c , the column floats upward, maintaining always the appropriate proportion of the mass above water. Thus the bottom of the column b must rise to b' in order that the top c may be maintained at c' . As the melting of the ice from the top proceeds, the column of ice continues to rise and the top can be reduced to water level d only when the ice is all melted.

Consider further the material which replaces the rising column of the ice. As the bottom of the column b rises to b' the space bb' is filled with material of the same density as that surrounding the ice. When removal of material has proceeded to such an extent that the top c is reduced to water level at d , the inflow of the denser material has replaced the lighter and the column de will have the same mass as the ice cb .

If the column bc illustrates rock of low density sustained in rock of high density, ac may represent mountains rising above sealevel. As the mountains are eroded away, the column rises so that much more material is removed from them than is represented by their reduction in altitude. The mountains may be baseleveled only when the supporting column has reached the density of the material surrounding it.

In applying this illustration several principles must be considered, some of which will strengthen and others modify this simple conception.

As erosion of mountains proceeds, isostatic equilibrium is maintained. Therefore, before baselevel is reached, a much greater amount of material is removed than that originally above sealevel. Field observation confirms this principle. The amount of material removed in the baseleveling process will depend on difference in the density of the eroded material and that of the material added to the lower part of the column by the isostatic adjustment.³

The rise of the column of rock of low density and the entrance of heavy

³ After this paper had left the writer's hands a volume by Nansen⁴ was received, which contains much significant information concerning isostasy. In this volume the claim is advanced that a balance, even more delicate than is advocated by the present writer, is maintained. Nansen shows (page 305) that under this assumption of delicate balance a mass of rock having a density of 2.6 at the surface, with a substratum of density 3.6, a thickness of 385 meters must be eroded to lower the surface 100 meters with respect to sealevel. If the density of the substratum is 3.0, 770 meters must be eroded to lower the surface 100 meters.

⁴ Fridtjof Nansen: The strandflat and isostasy (Videnskapsselskapets Skrifter. I. Mat. naturv. Klasse, 1921, No. 11), Kristiania, 1922.

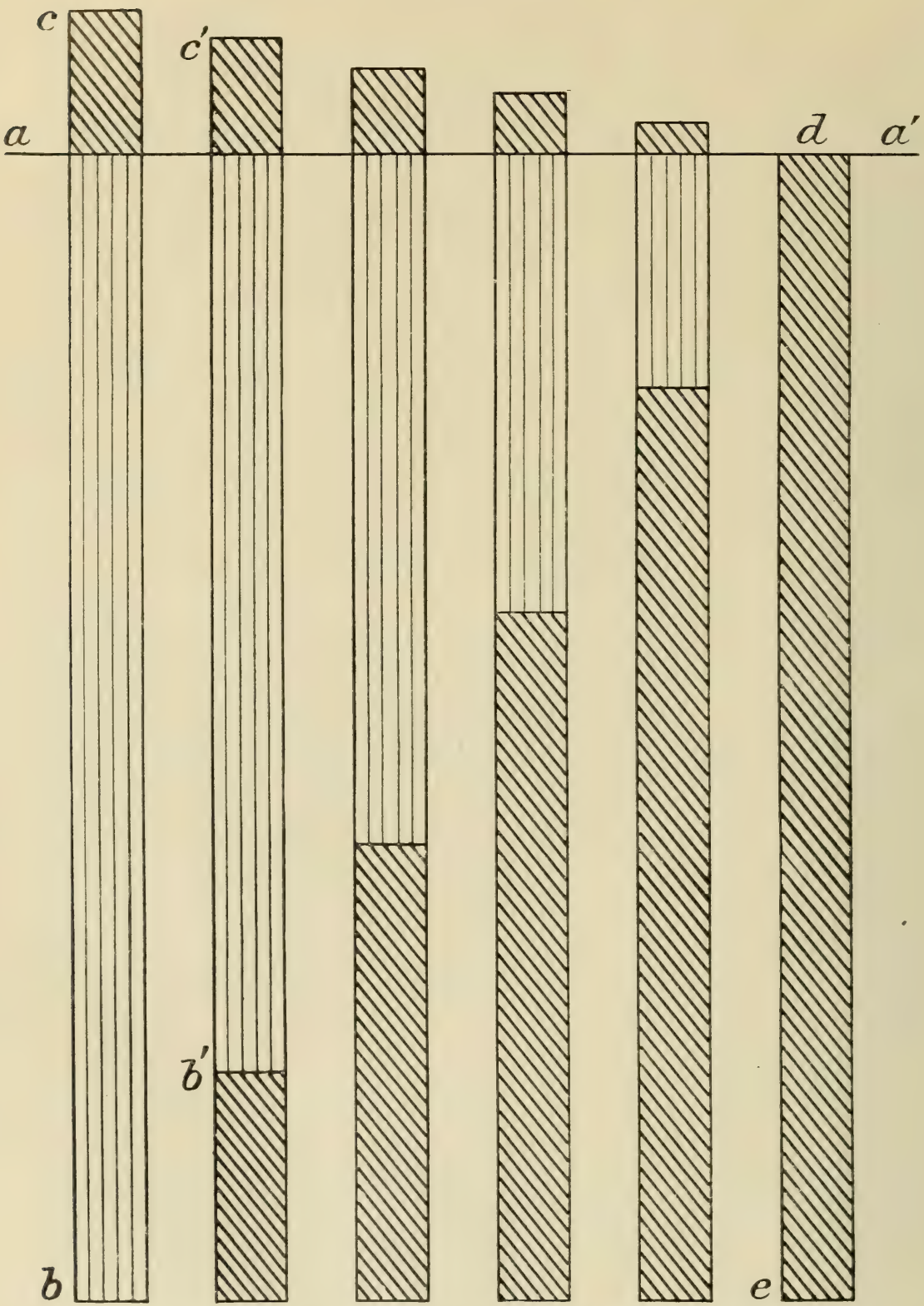


FIGURE 4.—Diagram illustrating the Relation of Erosion to the Rise of a Mountain Block

material beneath it has two important effects: First, the isogeothermal planes are raised farther than they would be by the expansion alone of the material of the block under increasing temperature, for hot rock is raised bodily into a position where its temperature is above normal and where its density tends to increase because of lowering temperature; second, the material added to the column from below to take the place of the material of less density of the rising block may be dense and therefore tend to check the rise. It will be pointed out (page 298) that change in density may reverse crustal movement and cause a rise of the surface about 1,200 feet under the conditions postulated. The tendency of the earth column to "float" when its density is decreased makes possible a much greater rise as the top is eroded, and Lambert shows in the accompanying paper that the removal of 10,000 feet of sediments will allow of 209 to 376 feet more. Probably many times that amount has been eroded, and it is probably safe to place the rise of the surface due to relief of pressure and lessening density as about 2,000 feet.

From the appended computation by Van Orstrand it appears that the effect caused by changes of temperature due to elevation or depression of parts of the earth's crust lags so far behind these changes that fixity in position of isogeotherms is not to be expected at any time in a region of repeated crustal oscillation, such as that of the Southern Rocky Mountain Province. As the rocks of the subsiding Cretaceous Basin, once at the surface and therefore cool and correspondingly dense, were buried their temperature increased, their density decreased, and in time the downward movement was halted; but, on account of slow transfer of heat, this halting occurred only after a subsidence of about 10,000 feet. Thereafter the increasing heat would tend to still further decrease the density of the material in the earth block and cause the surface to rise, as shown by Bowie.⁵

The effect on volume due to change in temperature may be computed. Accepting Bowie's figure⁶ for cubical expansion of rock as 0.000038 for 1 degree centigrade, and the principle that the increased volume is expressed in linear expansion because the rocks can expand only in an upward direction, and accepting further an increment of temperature of 1 degree centigrade for 100 feet, by a depression of 10,000 feet the earth block is lowered to a position where it is 100 degrees centigrade cooler than is normal. The return of the temperature to normal produces an expansion of about 1,200 feet in the 60-mile block—that is, $0.000038 \times$

⁵ William Bowie: The earth's crust and isostasy. *Geog. Review*, vol. xii, 1922, p. 618.

⁶ William Bowie: Theory of isostasy. *Bull. Geol. Soc. Am.*, vol. 33, 1922, p. 285.

$100 \times 60 \times 5,280 = 1,203.84$. In other words, a rise of the surface of 1,200 feet may be attributed to expansion of material, leaving the greater part of the known rise to be accounted for in some other way.

As the surface *a* of the diagram, figure 3, is depressed 10,000 feet to *a'*, the isogeothermal plane *b* sinks to *b'*, where the normal temperature is 100 degrees centigrade higher than at *b*. The isogeotherm tends to rise, but this rise is so slow, because of the low conductivity in rocks, that reheating takes place after most of the sinking has been accomplished. However, when expansion under rising temperature begins, subsidence ceases; but, because of the 10,000 feet of new material, this balance is reached long before *b'* rises to *b*. As the temperature of the block increases, the surface *a* is lifted to position *c*, the maximum for the 60-mile block being 1,200 feet, and erosion still further lightens the block, allowing it to float up so that the isogeothermal plane *b* is raised to *b''*. Material from the side below the depth of compensation⁷ enters and forces up the lightened block. The tendency of the isogeotherm is now downward through the material (but upward relative to any fixed horizontal surface), but the lag in effect due to low conductivity allows considerable rise before cooling increases the density and reverses the movement.

The experiment with steel tape reported by Van Orstrand has a significant application to the yielding of solid matter under stress (and perhaps also to the change in density of rock under load). He shows that elongation of the tape under a load of less than one-twentieth of the breaking load and the return on relief of stress is many times greater than the change necessary in a column of rock to produce geosynclines and mountains.

One of the difficulties in explaining the formation of mountains under isostatic adjustment has been the apparent necessity of a zone of flow, while other lines of evidence call for a high degree of rigidity in the rocks. The rearrangement of matter in the steel tape suggests that transfer of rock in a solid state may take place readily enough to meet all requirements for the building of the Rocky Mountains without recourse to a zone of easily flowing rock.

Although relatively little is known of the behavior of rocks under conditions which prevail miles below the surface, other possible causes of subsidence of the Cretaceous Basin are elastic deformation of the rocks and actual compression of rock material under load. A measure of the elastic yielding under the conditions of temperature, rigidity, etcetera, prevailing at the surface has been computed by Walter D. Lambert, of

⁷ William Bowie: The earth's crust and isostasy. Geog. Review, vol. xii, 1922, p. 621.

the Coast and Geodetic Survey, who shows that only a small percentage of the depression could be due to elastic deformation, leaving the greater part to be accounted for in some other way.

There are many other possible processes which might be discussed with profit, such as the change in crystal form of rock-forming material under varying conditions of heat and pressure and the expulsion under certain conditions of such mobile material as water and gas; but, as I have not been able to find much quantitative data bearing on these problems, discussion of them is omitted. Other significant problems have to do with possible fluctuations of sealevel.

It is well known that sealevel may rise and fall as the capacity of the ocean basins changes, and that altitude as reckoned from sealevel may change without any movement of the land whose altitude is measured. Doubtless some of the apparent subsidence of the Cretaceous Basin was due to rise in sealevel. It has also been pointed out that material eroded from the uplands and transported to distant regions may affect the position of sealevel, under the well-known principle that a landmass tends to draw the sea water toward it. If the rocks of the continents and basins were of equal density and the landmasses above sealevel be reckoned as excess material, the rise of sealevel on the flanks of highlands would be a large factor in determining apparent altitude; but under the hypothesis of isostatic adjustment, which calls for equal mass beneath highlands and basins, the change in sealevel because of land attraction is found to be only a few feet. According to computations kindly furnished by Mr. Lambert, a continental mass in isostatic adjustment will affect sealevel so little that, for purposes of this paper, the effect may be neglected. The approximate upwarp of the water surface at the middle of a continental mass of average density, 2.83, is as follows:

Elevation of continent above mean sealevel,	Warping of geoid under complete compensation. Depth, 100	
	kilometers, or about 62 miles.	
Feet		Feet
0		33
5,000		63
10,000		93
15,000		123

CONCLUSION

In conclusion, two critical considerations may be emphasized: First, changes in density due to flow of heat are slow and they usually oppose crustal movement, halting and finally reversing it. Second, a column of rock made light by increased temperature and decreased density may rise

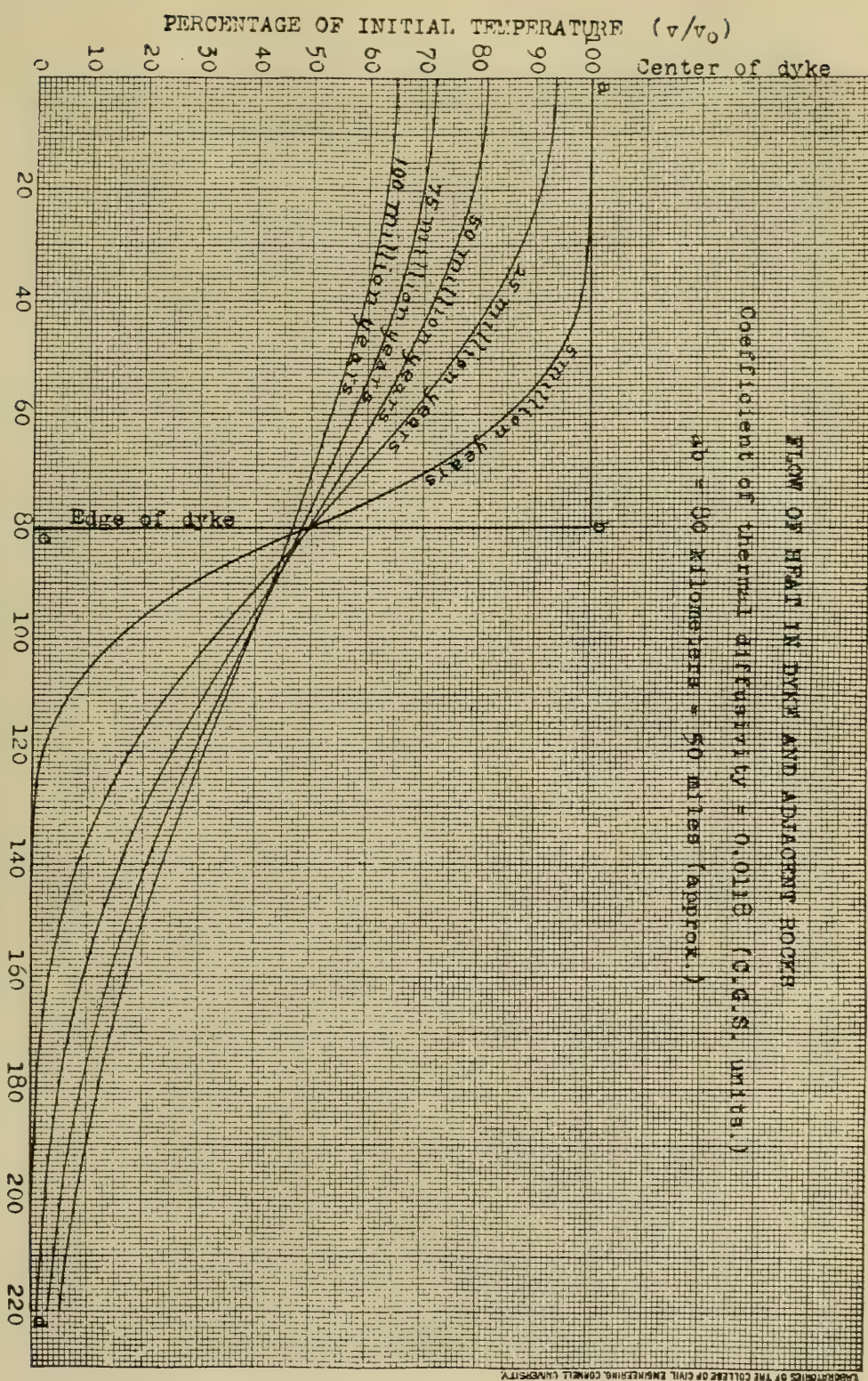
as the top is eroded away, in the manner illustrated by ice, which rises in water as the upper part is melted. Because of the tendency of the column of rock to behave as a floating mass, the rise is not restricted to the mere expansion of the mass. A search for cause of the building of the Southern Rockies fails to reveal evidence of lateral thrust of sufficient magnitude to account for them by crustal shortening. Field observations indicate that they were formed chiefly by vertical uplift. Considering available sources of information, local forces acting within the crust beneath these mountains seem competent to build them without calling on forces originating at a great distance.

The following "Notes on isostasy," by C. E. Van Orstrand, of the United States Geological Survey, and "The elastic yielding of the earth's crust under a load of sedimentary deposits," by Walter D. Lambert, of the Coast and Geodetic Survey, were prepared for this paper and should be considered parts of it.

NOTES ON ISOSTASY; BY C. E. VAN ORSTRAND

The question as to the movement of isogeotherms can be answered by reference to the diagram, which gives the distribution of temperatures in a dike and the adjacent rocks for different time intervals. The dike is assumed to be of very great depth and length; the thickness is taken to be 160 kilometers, or about 100 miles. The entire dike is assumed to be at some constant temperature and the whole is suddenly injected between rocks whose temperature for convenience is assumed to be 0 degree. Points on the curves for given time intervals, say 5,000,000 years, represent the temperatures at that point, expressed in percentages of the initial temperature of the dike. For example, if the initial temperature of the dike was 1,000 degrees, the temperature at a distance of 90 kilometers from the center of the dike was $0.30 \times 1,000 = 300$ degrees. Twenty million years later the temperature at this point had risen to about 410 degrees, as shown on the 25,000,000-year curve. The temperature at the center of the dike had been lowered only about 60 degrees in this same time interval. At the end of 100,000,000 years the temperature at the center was about 650 degrees, a reduction of 350 degrees.

The calculations do not apply rigorously to the elevation and subsidence of a mountain range, for the reason that heat flow from the bottom of the block has been omitted, and, furthermore, the block is not put instantly in place, as is here supposed. However, with these corrections, there will still be a very considerable lag of the isogeothermal surfaces during elevation and subsidence.



LABORATORIES OF THE COLLEGE OF CIVIL ENGINEERING, CORNELL UNIVERSITY

FIGURE 5.—Flow of Heat in Dyke and adjacent Rocks

The initial distribution of temperature is represented by a, b, c, d.

It is obvious that without surface changes capable of initiating movement, such as the changes in load by erosion and deposition, internal forces tending toward deformation of the earth's surface must ultimately reach equilibrium. Such a condition of affairs could be reached only when erosion and deposition are absent, as on the moon. The height to which mountains can rise on a globe like the moon, on which there is no atmosphere, is dependent on initial temperature, force of gravity, and plastic properties of the materials constituting the isostatic shell; they should, therefore, be capable of determination by the methods of mathematical analysis.

Prof. R. S. Woodward⁸ has solved a problem which gives a measure of the effect of change in surface temperature on the earth. He assumes that the mean annual temperature over the Bonneville Basin was raised 10 degrees Fahrenheit. The change in elevation of the basin due to the change of only 10 degrees Fahrenheit in the mean annual temperature for different time intervals is as follows:

Time interval.	Changes in elevation.
Years	Feet
10,000	0.41
100,000	1.28
1,000,000	4.06
50,000,000	28.7
100,000,000	41.

These figures show that even moderate fluctuations in temperature on the surface of the earth, covering long intervals of time, produce forces which tend to check subsidence and initiate elevation, or, conversely, they may check elevation and initiate subsidence.

A rise of 25,000 feet in 5,000,000 years, as shown by Lee for the Rocky Mountains, is equivalent to a uniform rise of 0.005 foot per year, or an extension,

$$e = 1,578 \times 10^{-11},$$

in a column of rock 60 miles in height. That is,

$$60 \times 5280 \times 1578 \times 10^{-11} = 0.005 \text{ foot,}$$

or a little less than 1/16 of an inch in one year.

The rocks in the crust of the earth are always in a state of strain; consequently we are not concerned with initial strain, but a subsequent strain or flow in the rocks due to carrying loads for long intervals of

⁸ R. S. Woodward: On the elevation of the Bonneville Basin by expansion due to change of climate. U. S. Geol. Survey, Mon. I (Lake Bonneville, Gilbert), 1890, pp. 425-6.

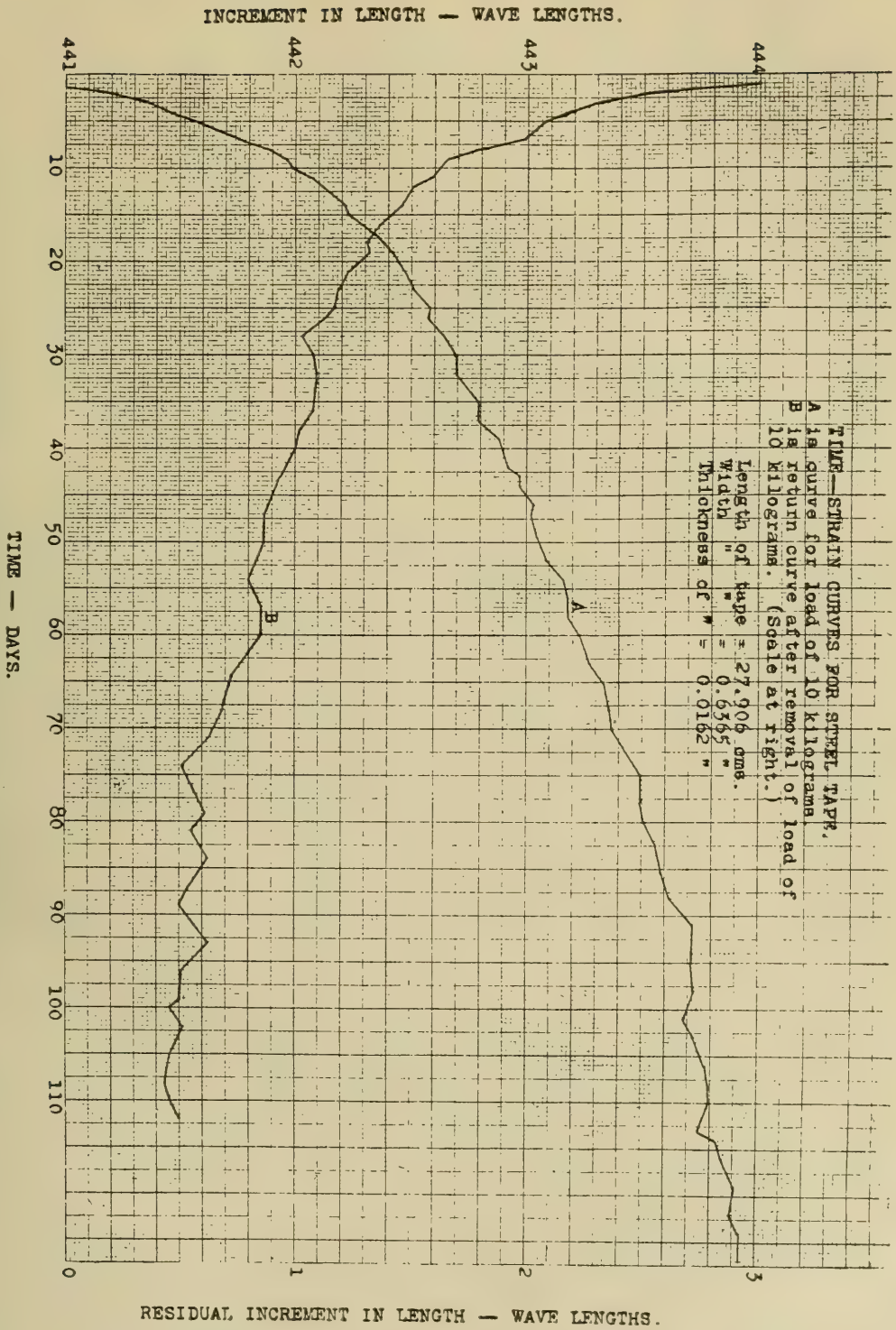


FIGURE 6.—Readjustment of solid Material under Strain

time. Some indication of the behavior of rock material under continuous load is given by an experiment conducted a few years ago by Mr. H. D. Ayres in collaboration with the late Dr. George F. Becker and myself. A steel tape—cross-section, 0.0162×0.6365 centimeter; length, 27.906 centimeters—was subjected to a load of 10 kilograms (less than one-twentieth of the breaking load) for a period of 126 days and then released. On account of certain defects beyond our control, we were unable to decide whether or not the tape returned to its original length, but the following results on the increment in length of the tape with time, due to the load of 10 kilograms, show that substances like steel do not necessarily reach equilibrium when subjected to continuous stresses well within the so-called elastic limit. The results are contained in the following table and platted in figure 6:

Load, 10 kilograms.		No load, following load of 10 kilograms.	
Time interval.	Total increment, wave lengths.	Time interval.	Total increment, wave lengths.
5 minutes.....	439.82	5 minutes.....	4.31
1 hour.....	440.12	1 hour.....	3.89
1 day.....	440.89	1 day.....	3.00
10 days.....	441.99	10 days.....	2.63
19 days.....	442.42	19 days.....	1.32
30 days.....	442.69	30 days.....	1.08
39 days.....	442.88	40 days.....	1.00
49 days.....	443.04	50 days.....	0.87
60 days.....	443.23	60 days.....	0.85
80 days.....	443.51	79 days.....	0.61
101 days.....	443.68	100 days.....	0.46
114 days.....	443.82	108 days.....	0.44
126 days.....	443.93	112 days.....	0.50

Curve A of figure 6, which represents the data in the first two columns of the table, shows that the tape would have continued to stretch for a much longer interval of time. On the other hand, the data in the last two columns of the table, represented by B in the diagram, shows that the tape had almost returned to its original length at the end of 112 days. The temperature of the tape during these tests was 27.1 degree centigrade (80.8 degrees Fahrenheit).

It was found by means of a least square solution, using 12 observations between the 101st and the 126th days, inclusive, that the tape lengthened during that time at the rate of 0.00944 wave lengths per day. Considered as an extension, we have,

$$e' = \frac{0.00944 \times 5876 \times 10^{-8}}{27.906} = 198\,772 \times 10^{-13} \text{ per day.}$$

Reducing the extension in the column of rock, 60 miles in height, to a daily basis, we have for the ratio of the two extensions,

$$\frac{e'}{e} = \frac{198\ 772 \times 10^{-13}}{43\ 241 \times 10^{-15}} = 460;$$

in other words, the tape increased in length by a process of flow (elastic after-effect) during the interval, 110-126 days, at a rate which was 460 times the elongation in a column of rock 60 miles in height, necessary to produce a mountain range 25,000 feet in height in 5,000,000 years by the flow of material into the base of the column.

A load of 10 kilograms on the tape produced a stress of about 13,800 pounds per square inch, which is the same as the pressure at the bottom of a column of water 31,800 feet (6.0 miles), or a column of rock 12,700 feet (2.4 miles) in height. Considered as a mechanical property of matter, therefore, there would seem to be nothing exceptional in the development or erosion of a mountain range by the process of isostatic adjustment. The mechanism is due to the conduction of heat and the redistribution of weight on the crust of the earth brought about by evaporation, changes in mean annual temperature, deposition of sediments, redistribution of large bodies of water, etcetera. The rocks within the isostatic shell are always under the influence of a system of forces which is never in equilibrium, and the resultant of this system of forces tends always to cause the rocks to flow very slowly, in the direction of least resistance.

ELASTIC YIELDING OF THE EARTH'S CRUST UNDER A LOAD OF SEDIMENTARY DEPOSITS; BY WALTER D. LAMBERT

The strata principally concerned in the elastic yielding of the earth's crust are doubtless chiefly composed of material similar to the basic intrusive rocks. The ranges of the elastic constants of the four specimens of such rock tested by Adams and Coker⁹ were

μ = modulus of rigidity	from 2.670×10^{11} to 4.380×10^{11} C. G. S. units
κ = modulus of cubic compressibility	from 4.650×10^{11} to 7.329×10^{11} C. G. S. units
E = Young's modulus	from 6.71×10^{11} to 10.80×10^{11} C. G. S. units

⁹ F. D. Adams and E. G. Coker: An investigation into the elastic constants of rocks, more especially with reference to cubic compressibility. Washington (Carnegie Institution), 1906, p. 69.

For an average value we may take in round numbers

$$\begin{aligned}\mu &= 3.6 \times 10^{11} \text{ C. G. S. units,} \\ \kappa &= 6 \times 10^{11} \text{ C. G. S. units,} \\ E &= 9 \times 10^{11} \text{ C. G. S. units.}\end{aligned}$$

The ratio between the adopted values of μ , κ , and E implies that Poisson's ratio, σ , is equal to $\frac{1}{4}$. The average value of σ was in fact very nearly $\frac{1}{4}$ for the specimens tested.

Let us consider a section of the earth's crust extending down to the zone of flow, say 100 kilometers (62.1 miles), and suppose that on this is placed a load of sediment 10,000 feet (3,048 meters) thick and of density 2.3, about that of sandstone. There are three limiting cases which may be readily computed and which may throw light on the elastic yielding of the crust.

(1) Suppose the rock to be compressed as a fluid, with no rigidity or resistance to shear—that is, $\mu = 0$ —but having a resistance to change of volume measured by $\kappa = 6 \times 10^{11}$ C. G. S. units; and suppose further that this fluid rock is confined by unyielding walls at the bottom and sides, so that the only yielding is in the vertical direction and the pressure is, of course, uniform in all directions. The relative decrease in length, ϵ , is given by the formula

$$\epsilon = \frac{p}{\kappa}, \quad (1)$$

where p is the pressure per unit area. This case, while probably the most artificial of the three as regards what would happen within a short time after the sudden application of the pressure, may yet give a fair approximation to what would happen if time were allowed for the rock to flow—that is, we know that under the long-continued application of force the rock may lose its rigidity and μ become equal to zero.

(2) Suppose the section of crust to be supported at the bottom, but to be unconfined at the sides, the pressure being applied at the surface as before. The problem is then one of compression under the usual experimental conditions, and we have

$$\epsilon = \frac{p}{E}. \quad (2)$$

(3) Suppose the section of crust to be supported at the bottom, and that just enough pressure is applied at the sides to keep them from bulging out. This condition is one not usually contemplated in the theory of elasticity, but the formula for it may be deduced from the fundamental equations,

$$\left. \begin{aligned} E\epsilon_1 &= p_1 - \sigma(p_3 + p_2), \\ E\epsilon_2 &= p_2 - \sigma(p_1 + p_3), \\ E\epsilon_3 &= p_3 - \sigma(p_1 + p_2). \end{aligned} \right\} \quad (A)$$

In these equations E and σ have the meanings previously given; p_1 , p_2 and p_3 denote the stresses (positive for tension, negative for compression) per unit area in three mutually perpendicular directions; ϵ_1 , ϵ_2 and ϵ_3 denote the relative changes of length (positive for elongation, negative for contraction) in the same respective directions. Let $-\epsilon_1 = \epsilon$ and $-p_1 = p$ be the relative change of length and the pressure in the vertical direction. By hypothesis $\epsilon_3 = \epsilon_2 = 0$, since there is no lateral yielding. The second and third of equations (A) then give

$$p_3 = p_2 = \frac{-\sigma p}{1 - \sigma},$$

which, substituted in the first of (A), gives

$$\begin{aligned} \epsilon &= \frac{p}{E} \left(1 - \frac{2\sigma^2}{1 - \sigma} \right), \\ &= \frac{5p}{6E}, \end{aligned} \quad (3)$$

since $\sigma = 1/4$.

The 10,000 feet of sediment exert a pressure of 6.88×10^8 dynes per square centimeter. The value of ϵ found from formulas (1), (2), and (3) are to be multiplied by the assumed thickness of the crust in order to obtain the yielding in linear units. The numerical results are then

Depression of 100-kilometer Crust by Sediments 10,000 Feet thick

Case (1)	Case (2)	Case (3)
Formula (1)	Formula (2)	Formula (3)
115 meters	76 meters	64 meters
376 feet	251 feet	209 feet

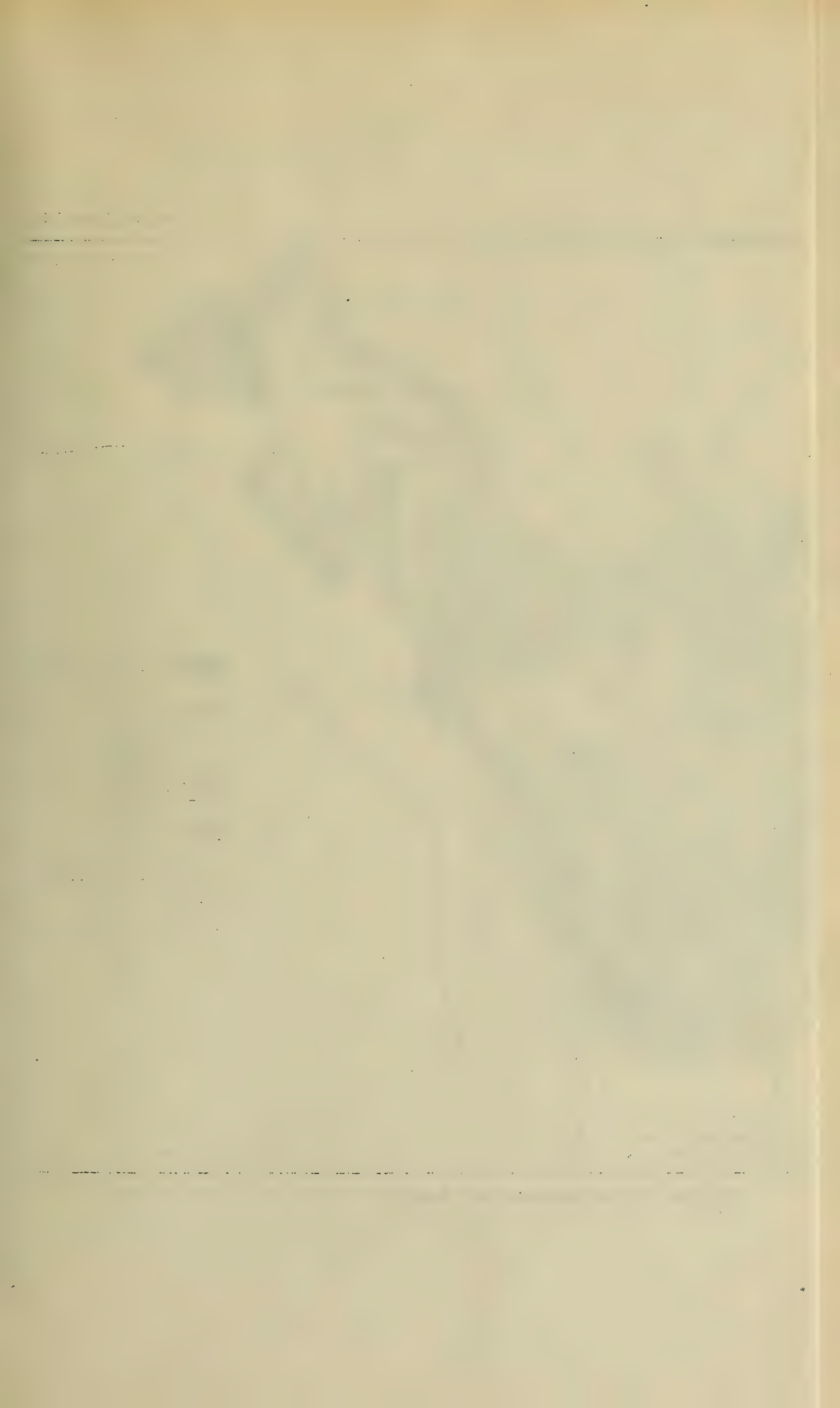
These results are based on the assumption that the elastic moduli remain constant. The velocities of earthquake waves indicate that the moduli increase,¹⁰ and that at a depth of 100 kilometers we have κ equal to 9×10^{11} , or 10×10^{11} C. G. S. units, with the other moduli in proportion. The figures given above for the depression of the crust should, therefore, be diminished, perhaps, 20 per cent.

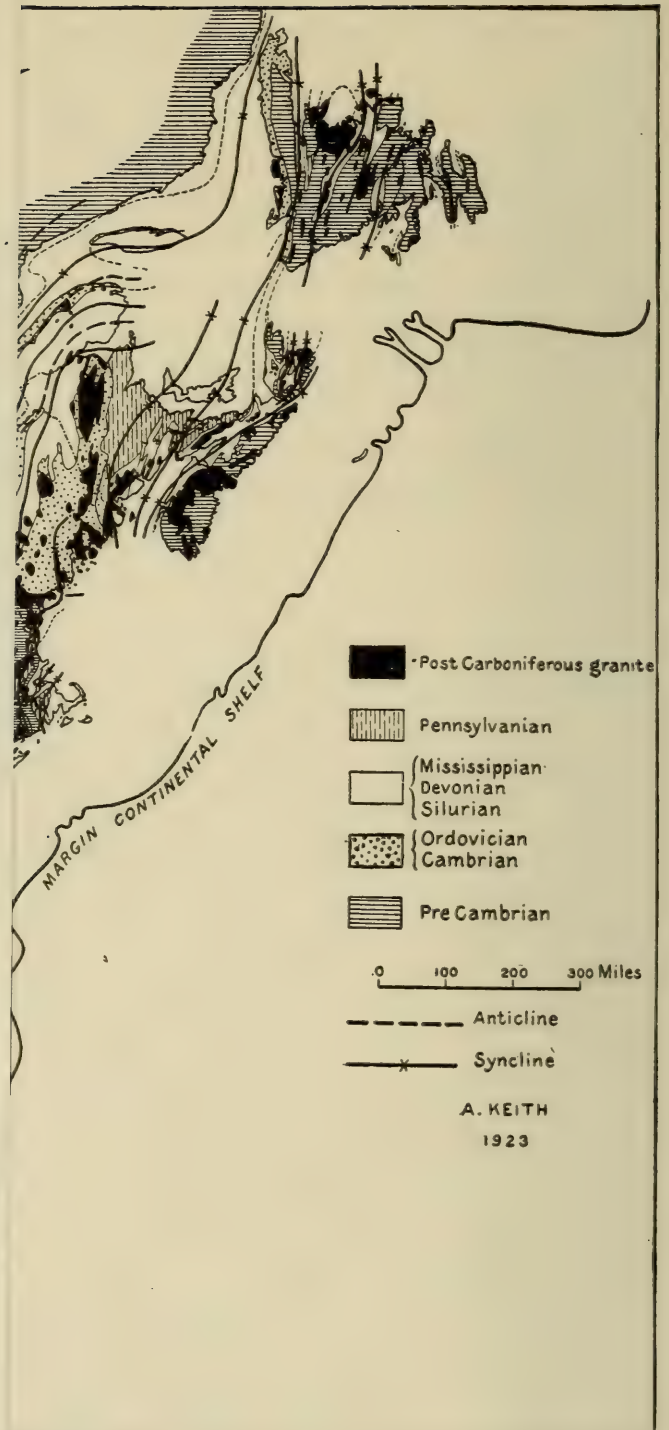
Furthermore, these formulas suppose the section of crust considered to

¹⁰ C. G. Knott: The propagation of earthquake waves through the earth, and connected problems. Proceedings Royal Society of Edinburgh, vol. 39, pt. ii (1918-19), p. 169.

be cut off from its surroundings, deriving no support from them. Uniform pressure over the surface then gives the same yielding at all points of the section and for sections of all sizes. For any small section connected with the surrounding crust, the yielding computed by formulas (1), (2), or (3) is much too great.

If, however, we consider a section having a very large area and connected, as in nature, with its surroundings, these formulas, particularly case (2) formula (2), give an indication of the approximate yielding to be expected in the *center* of the area; for the outer portions of the area are so pressed down by the load on them that they afford little support to the central portion, and the latter yields almost as much as if it were severed from its surroundings. The extent of the area that may be considered "large" must evidently increase with the rigidity of the crust. For extremely large areas, the curvature of the earth's surface must also be considered, and its effect is to diminish the yielding somewhat.





REGION

OUTLINES OF APPALACHIAN STRUCTURE¹

BY ARTHUR KEITH

(Presented before the Society December 29, 1922)

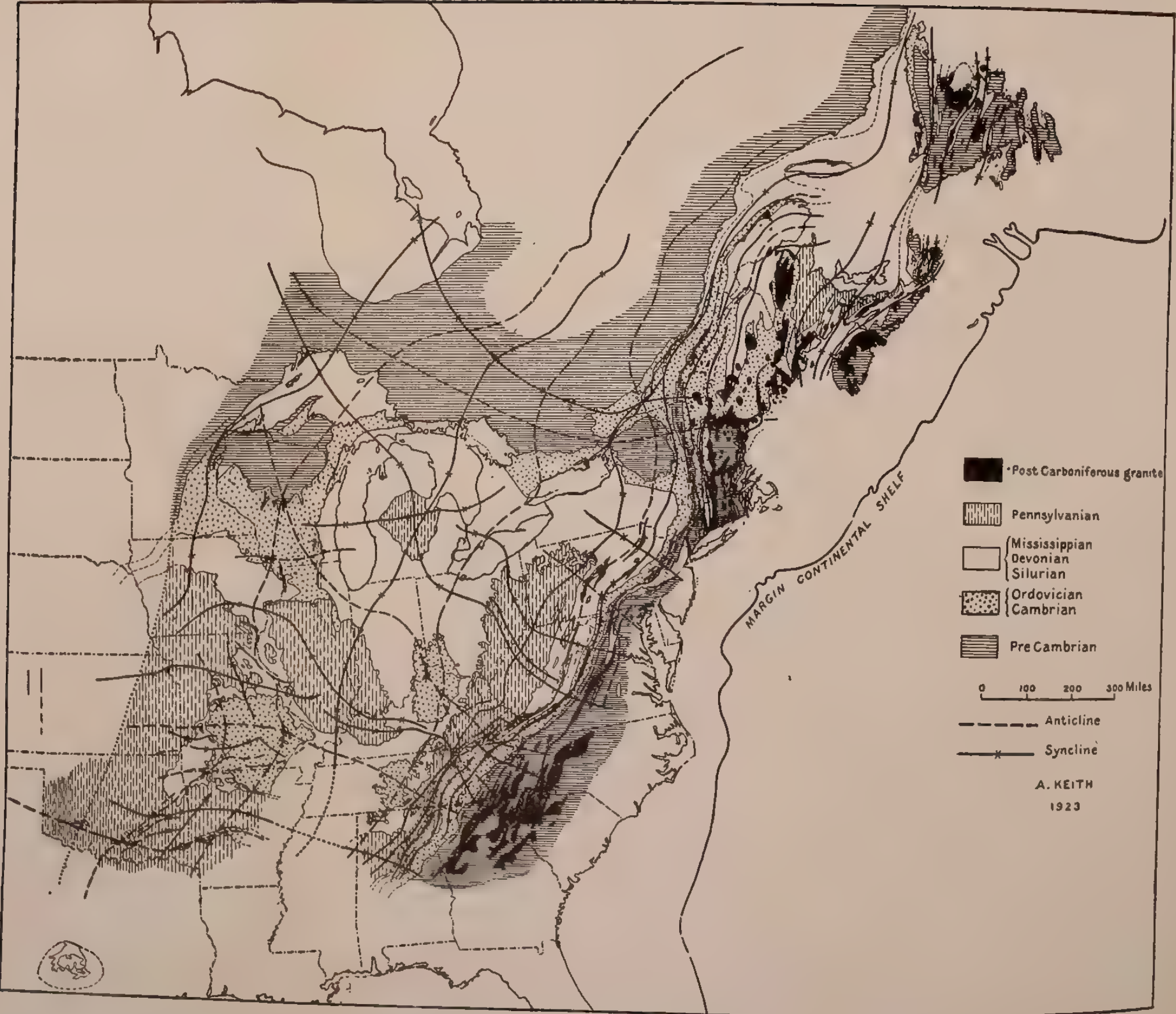
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GEOLOGIC MAP OF APPALACHIAN REGION

A. KEITH
1923

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INTRODUCTION

The subject of Appalachian structure is one of the most interesting in geology in that it affords the greatest example of mountain structure in the world. All stages of deformation from undisturbed rocks to beds folded, overturned, broken, mashed, and metamorphosed are seen throughout the entire length of the system, 2,000 miles from Alabama to Newfoundland. The connecting links between the types of structure are finely exposed and the chain is complete. The rocks exposed range from earliest Precambrian to Tertiary, and the depths of the earth are laid bare in the heart of the range in a manner nowhere equaled.

The beginning of the study of the Appalachians practically coincides with the beginning of American geology about 100 years ago. The principal structures of the folded sediments were made known by the work of the Rogers brothers in Pennsylvania and Virginia about 80 years ago. Substantial contributions were made by many of the early geologists on the various State surveys, such as Hall, Emmons, Safford, Lesley, Smith, White, and Stevenson. Such leaders as Dana, Logan, Dawson, Selwyn, and Hitchcock added to Appalachian knowledge in important ways.

Systematic, detailed work was begun for the United States Geological Survey in 1885 by Pumpelly, Russell, Willis, Darton, Dale, and Hobbs; in 1887 by Hayes and Keith; and in 1889 by Campbell; and it has been carried on since that time by the Survey and by many individuals. In recent years many of the State surveys have done their shares of the detailed work. The present author has continued his work in the Appalachians each year since 1887, though with many interruptions of late, the first 20 years in the south, and in later years mainly in the north.

In the following discussion the attempt will not be made to present details, but only to state the general features and typical groups of facts which have controlled the local facies of the deformation. Next will be given the generalizations of the phenomena according to time and space. Following these, inferences will be drawn as to the direction, application, and method of transmission of the deforming forces. This will be followed by a brief statement of various theories of mountain structure and their application to the Appalachians. Finally, a theory will be presented as to the immediate nature of the deforming force and as to its ultimate source. The substance of the generalizations as to the strong deformation of the Appalachians and its cause was presented by the author in 1914 in his presidential address to the Geological Society of Washington. In the present discussion the surroundings of the folded belt are also analyzed, and the cause of the folding is more definitely set forth.

DEFINITION

The Appalachian folded belt is continuous from central Alabama to New Brunswick, in Canada, a distance of 1,500 miles. Its southern extension is covered by the Cretaceous and Tertiary deposits along the Gulf of Mexico, while at the north it passes beneath the Gulf of Saint Lawrence and crosses the island of Newfoundland, making a total length for the system in North America of 2,000 miles. If the general line of the Appalachians is extended across the North Atlantic it crosses the southern portions of the British Isles and thence passes into central Europe. It thus appears to be part of a great system of folding called the Armorican system by Suess, which has the same features and the same age as the Appalachian system. The extension of the Appalachians southwest of Alabama is problematical. Some geologists consider the Ouachita Mountains of Arkansas and Oklahoma to be the western extension of the Appalachians, in which case the latter would be bent nearly at a right angle. It seems to the author, however, that the Ouachita folds, while developed at the same time, rose on one of the cross-axes

which characterized the earth movements at the end of the Paleozoic. In Central America there seems as yet to be no mountain-building which can safely be connected with that of the Appalachians.

There has been little description or discussion by geologists in general of the width of the Appalachian system as a structural unit. It has commonly been considered to include the gentle folds of the great Carboniferous synclinorium lying just west of the strongly deformed belt and extending westward to the Cincinnati arch. No eastern limit has been assigned except tacitly by the discussion of the Paleozoic folded sediments but not of older rocks on the east. This has been due in the past to the lack of information concerning the pre-Paleozoic rocks and to the labor and difficulties involved in securing that information. The author has spent many years in the examination of the Precambrian rocks of the Appalachians with full realization of the important part which they have played in Appalachian deformation, and has in all his descriptions treated the eastern and older rocks as part of the Appalachians. The Appalachian system, in his estimation, is limited on the southeast by the Cretaceous cover of the Coastal Plain as far north as Hudson River, and in New England and Canada by the Atlantic Ocean. The Appalachian folds are strong where they pass beneath the sediments of the Coastal Plain or the Atlantic, and there is no indication that the original eastern limit of the system is visible.

A northwestern limit is very difficult to set, since the gentle folds produced at the end of the Paleozoic form a system integral with the Appalachians which extends across the Mississippi Valley to the Cretaceous rocks of the great Central Plains. Nowhere is it possible to draw a line which will separate great groups of rocks of unlike structure or even of unlike stratigraphy. The fold systems of that time are shown in plate 4. In Alabama and Tennessee at the south and in New York and Canada at the north the intensity of the folding diminishes rapidly northward at the margin of the Cumberland Plateau of the south and of the Adirondack and Laurentian mountains of the north. In those areas there would be the best opportunity for setting a western limit for the Appalachians. Folds of Appalachian type appear west of this line, however, even where it is most pronounced, while in the central Appalachians of Virginia and Pennsylvania strong Appalachian folds are found far to the west of it, and there is a gradual transition from the strong folds of the east to the gentle basins of the great Carboniferous synclinorium.

The strongly folded belt in Tennessee, Georgia, and the Carolinas has an exposed width across the strike of 270 miles; its width in Quebec, Maine, and New Brunswick is practically the same, and across New-

foundland it is about 280 miles. Between these maxima at the north and south the Cretaceous transgression reduces the visible width of the belt to about 80 miles near the Hudson. Over the entire width of the folded belt overturned folds and thrust faults prevail. In New Brunswick and New England Carboniferous sediments are involved in the eastern half of the folded belt. In Georgia and the Carolinas Carboniferous granites occupy great areas at the east. In Virginia and Pennsylvania no rocks later than Middle Ordovician are now visible east of the Blue Ridge. The distribution of the Carboniferous sediments and granites is shown in plate 4. The great width of the intensely folded belt is of enormous importance, as will be seen when the Appalachian deformation is considered in later pages in a quantitative way.

DESCRIPTION

FOLDS

The folds of the Appalachians are very long and straight. Many single folds are more than 100 miles long, and even this figure is far exceeded by some structures, such as the anticlines of the Blue Ridge in Virginia and the Green Mountains of Vermont. The folds are rarely symmetrical, but one side, usually the northwestern, has steeper dips than the other. In many cases the beds are pushed past the vertical until they are upside down, and both sides of the fold dip in the same direction. Out of these unsymmetrical or overturned anticlines develop breaks in the sequence, or thrust faults, which, as a rule, dip to the southeast, like the axial planes. Little brecciation or crushing attends these faults, and the strata both above and below the fault plane tend to have similar dips. Faults of another class, called overthrusts, have no clear relation to individual anticlines but cut across great thicknesses of strata. They are characterized by great horizontal motion and by the low dip of their planes. Locally, these faults have been folded and cut through by later faults.

SALIENTS AND RECESSES

The folds are close together and for great distances run almost exactly parallel. To the traveler through the country the strata upturned along the folds seem to run perfectly straight for mile after mile, but in reality they sweep in long parallel curves as if drawn with a radius around a common center. In four districts, about 400 miles apart, the sweep of the axes carries the folds around four great westward salients or projections from the average course of the system, which is from southwest to northeast. These are (1) near the junction of North Carolina and

Georgia; (2) in southeastern Pennsylvania; (3) northern Vermont and near-by Canada; and (4) the extreme eastern part of Quebec near Gaspé. A fifth salient is probably submerged in the Atlantic Ocean not far north of Newfoundland, and a sixth may be buried by the Cretaceous sediments of southern Alabama and Mississippi. Between the salients are corresponding recesses around which the folds curve in the opposite direction to the curves on the salients. The southernmost recess is partly shown in central Alabama, where the Appalachian rocks pass under the Cretaceous cover; a second recess shows about midway in the course of the Appalachians through Virginia; and the third appears in northern New Jersey and southern New York, these two being the best defined recesses on the mainland. The fourth and weakest recess lies in northern Maine and Canada about midway between Lake Champlain and Gaspé. The fifth recess is located under the Gulf of Saint Lawrence, probably about midway between Gaspé and the west end of Newfoundland; this is the deepest recess of all and also, of course, the least known. There appears to be a rhythm in these salients and recesses in that they are somewhat evenly spaced. They have a very important bearing on the question of the direction and application of the thrust which deformed the Appalachians.

SOUTHEASTWARD INTENSITY

The Appalachian folds appear at the northwest in low, symmetrical anticlines and synclines. Toward the southeast the folds become higher, their beds dip more steeply, and their axial planes are more and more overturned toward the northwest. Many of the anticlines are broken by faults which dip to the southeast, and the upthrust portions are shoved from the southeast over on the synclines at the northwest. Locally this process was carried to excess, as, for instance, in northern New York and Vermont and adjacent Canada, and also at the opposite end of the system in Tennessee, Georgia, and Alabama. In both of these regions few, if any, of the anticlines have escaped being heavily faulted. Many of these faults exhibit great horizontal motion and low, eastward dips. These are especially numerous along the junction of the Appalachian Valley and the Appalachian Mountains which extend southeast of the valley. Viewed in a very broad way, the folds and faults have so raised the Appalachian rocks that, beginning with the nearly flat strata of the Appalachian plateaus, successively lower and older rocks appear toward the southeast until the very roots of the range are laid bare in the Green Mountains of the north and the Blue Ridge of the south and in the adjacent plateaus lying east of those mountains.

METAMORPHISM

In addition to the visible bending and fracturing of the Appalachian strata, deformation has also taken the form of metamorphism in which new minerals have partly replaced the old ones. This form of yielding to pressure has one large feature which is common to the other forms of yielding—that is, it grows more intense toward the southeast. There are no traces of this result in the horizontal rocks of the plateau, but the new minerals begin to appear along the southeastern portion of the Appalachian Valley and increase rapidly until east of the Blue Ridge and in similar situations at the north scarcely any of the minerals of the rocks retain their original forms. By this process limestones were transformed to marble; shales to slates and schists; sandstone to quartzites; and granites and igneous rocks to gneisses and schists. Sediments that contained clay, feldspar, or calcite were more readily altered than other strata, and basic igneous rocks formed schists more freely than rocks like granite. Most of this metamorphism took place in direct connection with the formation of shear planes during deformation, but an appreciable amount was due to the heat and solutions from batholiths, and still a third variety was the static result of pressure with no differential motion.

COMPETENCY OF BEDS

The individual rocks of the Appalachian vary enormously in the manner of their yielding to pressure. The geologist in the field soon perceives that thin-bedded rocks, like shales, slates, and schists, yield readily in small folds with dimensions from a few feet down to minute wrinkles. Heavy beds of solid quartzite, sandstone, or dolomite are bent in broad folds measured by hundreds of feet or by miles. The arch of Powell's Valley in Tennessee, for instance, is 6 miles across and is maintained by massive dolomite capped by massive limestone, conglomerate, and sandstone. Similar folds are found in the Cambrian quartzites of Iron Mountain in Tennessee and the Silurian sandstones of eastern Pennsylvania. The contrast in manner of yielding between shales and sandstones can frequently be seen in a single hand specimen. This relation is summed up in the statement that the thick massive beds are competent to resist pressure, while the thin beds are not.

Accordant with the foregoing principle are the variations in degree of metamorphism shown by the different rocks. Rocks containing argillaceous matter, whether in large deposits of shale or in thin seams between other rocks, were readily deformed and also readily metamorphosed. Thus, in a series of interbedded sandstones and shales, the shale may

have been well metamorphosed to phyllite or schist, while the sandstone was only silicified. Not only were some, like pure limestone, readily metamorphosed to marble, but in that process their strength was overcome and they flowed freely into the cracks and openings of more rigid and massive beds like quartzite or dolomite. This result is strikingly shown in some of the older marbles of western New England. In many of the quarries it is clear that a given marble has been in the zone of flowage for calcite marble, while the included dolomite layers were still in their zone of fracture. These features of rupture and flowage are so beautifully shown in many of the Vermont quarries that the region will become classic.

EFFECT OF LOAD

Another generalization relates to the effect of load in determining the kind of folding. Thin-bedded rocks like shale, as has been stated, fold readily—so freely, in fact, that the mere removal of a score or two of feet of overlying rock in a ledge will cause the underlying beds to buckle and lift. This fact shows that the rocks of the earth's crust, even close to the surface, are under a compression which is sufficient to condense them materially. The well known expansion of blocks when loosened in granite and marble quarries shows the same thing. It is, therefore, obvious that a load of thousands of feet of overlying rocks will condense and restrain the lower layers; their freedom of movement upward into folds when laterally compressed grows less as the overlying rocks are thicker. The pressure due to the weight of the upper rocks is added to the pressure of the mountain-building forces, and together they may be sufficient to overcome the strength of the rocks (as in the Vermont marbles) where neither force alone would be sufficient. Thus, a rigid bed when held down by a great thickness of shale above may be forced into broad folds, while the same rigid bed without much load above it may be so free as to be broken by faults rather than to be folded. The Knox dolomite of Tennessee exhibits both of these conditions and results. The maximum thickness of sediments is about 30,000 feet, and all, from top to bottom, are folded.

BEDDING SLIP

The importance of bedding planes in rocks is twofold. As was stated above, thin-bedded rocks with numerous planes are less rigid and consequently fold freely. In addition the bedding planes form natural surfaces of parting, and along these the layers slip in adjustment to folding. Inspection of any set of folded beds shows clearly a large amount of sliding of one layer over another. This is theoretically necessary in

folding and it is abundantly visible in fact. In igneous rocks, however, there are no such initial parting planes, and on this account igneous rocks as a class are more rigid and less deformed than sedimentary rocks. When the load and the lateral pressure are sufficient, however, the strength of even these rocks is overcome. They develop countless shear planes and motion ensues on them; the original crystals of the rocks are crushed and drawn out; new minerals are formed and schists and gneisses are thus produced.

EFFECT IN KIND OF YIELDING

If the foregoing generalizations are summed up and tested by the general character of Appalachian folding it is seen that there is complete accord. In Alabama, Georgia, and the adjoining part of Tennessee the chief component part of the stratigraphic column is the Knox dolomite. It is there underlain by thick shales and overlain by comparatively thin Ordovician, Silurian, Devonian, and Carboniferous strata. Consequently, there is an enormous development of thrust-faulting and comparatively little folding. Similar relations are found in northern Vermont and Canada, with the same result of tremendous overthrusting. In Pennsylvania, Maryland, Virginia, and northeastern Tennessee the general proportions of the stratigraphic column are reversed; the lower part of the section consists of various heavy quartzites, dolomites, and limestones overlain by great thicknesses of shale and sandstone. In this portion of the Appalachians, therefore, deformation is almost wholly by folding, and there are few faults except near the mountain border.

BORDER FAULTS

The narrow zone of faulting along the northwest border of the mountains is one of the most constant features of the Appalachians. Out of the entire extent of the range (1,500 miles on the mainland) only two regions are known where there is little or no faulting in that situation. These are in central Virginia and in southeastern New York. It is to be noted that these correspond precisely with the two major recesses in the Appalachian trend. A third place where the border fault may be absent is in northwest Georgia, also coincident with a smaller recess. The fact of minimum thrusting at these recesses contrasts most strongly with the maximum thrusting which is the fact at the three intervening salients. The conclusion can hardly be avoided that the forward advance on the thrust planes is the direct cause of the salient and that the lag where thrust is absent is the cause of the recesses.

HEIGHT AND DEPTH OF FOLDS

The faults of the mountain border zone are situated on the northwestern flank of the great anticline of the system, which manifests itself in the Sutton Mountains of Canada and their analogue in the Green Mountains of Vermont and Massachusetts, the Highlands of southern New York and New Jersey, the Reading Hills and South Mountain of Pennsylvania and Maryland, the Blue Ridge and Catoclin Mountain of Virginia, and the mountain belt between the Blue Ridge and the Iron, Great Smoky, and Frog Mountains of North Carolina and Georgia, and the extension of the belt into Alabama. This is the strongest known anticline of the Appalachians and is compounded of numerous lesser and local anticlines; it is perhaps no greater, but it is better known than the belt of uplift which lies still farther southeast. Equally continuous anticlines parallel the Blue Ridge-Green Mountain fold on the northwest, but they are lower and less intense and on them younger rocks form the surface.

The major synclines are also parallel to the anticlines but display much less variety. They are slightly deeper with reference to sealevel and contain younger rocks at the southeast, but they held a similar position at the beginning of the Appalachian revolution. The major syncline in the closely folded belt is much sharper but nearly as deep as the principal synclines farther northwest. The principal syncline southeast of the Blue Ridge anticline is sharply folded but is also very deep. In New England and Canada it carries Devonian beds down to sealevel and is deeper than any other syncline lying northwest of it. The syncline in Virginia, the Carolinas, and Georgia which has a similar position carries the Cambrian sediment to and below sealevel.

A series of cross-sections, therefore, brings out two facts, that the synclines differ only moderately in depth, while the anticlines are enormously different. From this it is necessary to conclude that the anticline is the constructively important feature of Appalachian structure, and that the syncline is merely the part left behind with the least change. This is precisely what should be expected from a theoretical consideration of a mass relieving itself from strain. The motion which affords the relief must necessarily be in the direction of least resistance, which is mainly upward. The same conclusion must be drawn from all experiments in the folding of artificial beds or in the laboratory deformation of actual rocks. In all of them, where there is any shortening, the relief is given by upward or outward motion; in other words, anticlines are always raised but synclines are not deepened.

When this conclusion is applied to the case of geosynclines it is seen

that their formation can not be due wholly to the ordinary processes seen in mountains caused by tangential shortening; the depression of the geosynclinal area and the uplift of the corresponding geanticline, of course, actually took place. The amount of departure of the beds from the horizontal is very much less, however, than in the folds due to lateral compression, and the kind of uplift is precisely that seen in the gentle doming of the Cretaceous and Tertiary beds around the Appalachians and the similar, though still slighter, doming of the later peneplains throughout the Appalachians. In these there is no evidence whatever of lateral compression, and a cause for them must be sought in which vertical movements or oscillations are the important feature. With this point in view it would perhaps be better to separate anticlines and synclines, due clearly to horizontal compression, from the low domes and basins which form geosynclines and geanticlines and which are, in the main, due to vertical movements.

FAN STRUCTURE

In many areas east of the Blue Ridge uplift variations are seen from the rule of Appalachian structures. In practically all Appalachian folds the axial planes are either upright or overturned toward the northwest, but folds overturned toward the southeast are found in a fairly well defined belt from Alabama to Massachusetts. Evidence of this is rather scarce and usually is obtainable only where sediments are involved with the gneisses and granites; it consists of folds closed and overturned to the southeast and of thrust faults dipping to the northwest. Near Washington secondary structures in gneisses exhibit the same features. These structures, taken in connection with the usual southeastward dips, form a great fan structure.

The fan structure is well defined at the following distances from the structural line of the border of the Appalachian Valley: Alabama-Georgia boundary, 75 miles; South Carolina-North Carolina boundary, 95 miles; North Carolina-Virginia boundary, 40 miles; Maryland, 40 miles; and Massachusetts, 90 miles. A second belt parallel to the above and about 50 miles to the southeast is seen in North Carolina, where the Appalachians are widest. Between Maryland and Rhode Island these structures are covered by the Cretaceous sediments or the Atlantic waters, and they reach the ocean again in the Boston basin. Their position in central Maine is not well known, for lack of detailed work, but they lie near the mouth of Penobscot River.

The belt of fan structures thus defined has an important relation to the large groups of granite batholiths. Where a considerable area is ex-

posed to the east of the fans, they are seen to lie between the batholiths. The detailed structure in the cases now known is that of a narrow synclorium with marginal faults on which the anticlinal masses were thrust over the synclorium from both sides. Compression and motion from both sides are clear, and the association of this fact with the neighboring batholiths strongly supports the theory that batholiths have caused mountain structures.

PRECAMBRIAN DIVERGENCE

A feature of importance in Appalachian folding is the divergence of structural trend exhibited in the folds involving Precambrian rocks. These folds, and the allied faults and metamorphism, locally contain included bodies of Paleozoic rocks. They also characterize the Precambrian in areas worn down far beneath the Paleozoic beds. Some of the structures plainly antedate intrusive masses of Precambrian age and are thus themselves Precambrian. It is probable, therefore, that where Paleozoic rocks have structures parallel to these the post-Paleozoic structures are posthumous, and that the Paleozoic deformation was controlled by the Precambrian structure lines. The trend of the Precambrian structures departs materially from those of the Paleozoic in most of the Appalachian range. There is an approach to parallelism along the border of the general Paleozoic mass, but southeastward in the interior of the Precambrian area differences of 10 or 20 degrees in trend are common. The Precambrian trend is more nearly north and south than the Paleozoic trend and in western New England, where the latter is nearly north and south, the Precambrian trend is distinctly west of north. In western Massachusetts the serrate outline of the Paleozoic and the northwest trend of the Precambrian units are strongly brought out. Similar relations hold in southern Pennsylvania, Maryland and Virginia, and the Carolinas, and wherever Paleozoic rocks are involved the control of the structures of the Precambrian over the Paleozoic structures is obvious.

TRIASSIC TREND LINES

Although the structures of the Triassic are not classed with those of the Appalachians, they have features in common, namely, the trend of the structures and the control of the structures by the Precambrian. The very preservation of the Triassic beds is due to the faults and the tilting forced on them by the Precambrian rocks. This is well brought out in Massachusetts, New York, and Pennsylvania, and is especially clear in Maryland just north of the Potomac. The trend of the Triassic

basins parallels that of the Paleozoic folds in a striking manner as far as the Triassic beds are known, and the Triassic faults extend far beyond the Triassic sediments with trends parallel to the Appalachian structure. The Triassic trends plainly show the Virginia and New York recesses and the Pennsylvania salient, but the Triassic beds do not reach far enough to exhibit the northern Vermont or northern Georgia salients. As far as they at present extend, however, the correspondence of the Triassic and Paleozoic trends is so complete that they must have a cause or a factor in common. Inasmuch as the Triassic basins and structures are directly controlled by the trends and vertical movements of the basement (mainly Precambrian rocks), we can hardly escape the conclusion that this same control was exercised on the Paleozoic movements by the Precambrian basement. Thus the three factors, (1) divergence of Precambrian structures, (2) control of Triassic structure by Precambrian, (3) parallel trends of Paleozoic and Triassic structures, combine to show the dominant influence of the Precambrian basement on all the structures of the Appalachian region. Even in the Tertiary and Pleistocene deformations the general axis of uplift is roughly the same as for the Precambrian, Paleozoic, and Triassic. This is precisely what should have been expected; if the Precambrian rocks were so distributed or of such a nature as to exercise a control during one epoch, the same factors would tend to produce it at later epochs.

SYSTEM OF BATHOLITHS

A matter of prime importance in the distribution of the various facts of the Appalachians is that of the intrusive masses, or batholiths. A generalized mapping of these for the southern Appalachians was given by the author on the geologic map of North America,² and large numbers of them have been mapped by various geologists in New England and the eastern provinces of Canada. In the southern Appalachians the batholiths, mainly granites, extend across Georgia, North Carolina, and South Carolina. They are found for the most part in the Piedmont, and only in North Carolina and northern Georgia do they occur west of the Blue Ridge. There is a decided predominance of the batholiths in South Carolina, behind the North Carolina salient, and they barely reach the Alabama-Georgia recess. They are of late Carboniferous age, since they are deformed little or not at all by the Carboniferous deformation. On the Pennsylvania salient the Piedmont belt is very narrow, but a few batholiths of Carboniferous age appear. Northward from the New York

² U. S. Geol. Survey, Prof. Paper No. 71.

recess Carboniferous batholiths are numerous. In Massachusetts, New Hampshire, and southern Maine they cut Carboniferous rocks, and there is a considerable concentration of them in southern Maine and the White Mountains of New Hampshire back of the northern Vermont salient. In eastern Maine and New Brunswick similar batholiths are numerous and have been assigned to the Devonian because they cut Devonian rocks and are overlain by Carboniferous. These are situated behind the northern or Gaspé salient. The chief points of distribution of these batholiths are their concentration behind the great salients and their chief development in the northern and southern parts of the Appalachian chain, where deformation by shortening is demonstrably the greatest. The meaning of this will be discussed on later pages.

PRECAMBRIAN PLATEAU

The broad belt of little folded rocks which underlies the Appalachian plateaus and the Saint Lawrence Valley is a distinct unit of the Appalachian system. As has already been stated, the eastern boundary of the little folded belt is distinct as a whole in the southwestern and north-eastern parts of the system, but is less so in Pennsylvania and West Virginia. Outside of these States the boundary is so sharp as to challenge explanation. In New York and Canada the answer is not hard to find. The closely folded belt is occupied by a thick section of Lower Cambrian and Algonkian beds, while in the gently folded belt they are absent and the section shows mainly a thin development of Ordovician. In the Saint Lawrence Valley in southern Ontario and Quebec these sediments are nearly flat. They rise to the south and from beneath them emerges the plateau developed on Precambrian granites and gneisses. The rise of the Precambrian in this Adirondack dome is caused by one of the major cross-anticlines, and on its south side in the same way the Precambrian rocks of the Adirondacks pass beneath the Ordovician. North of the Saint Lawrence Valley the same general Precambrian plateau exists, and on it overlap the Lower Ordovician strata. This plateau at the base of the Paleozoic was reduced to a very even surface and doubtless was of correspondingly broad extent. The extension southward of this relation is thus more than probable through southern New York into Pennsylvania. In fact, the boundary between the sharply folded and little folded rocks is very plain in the lower Mohawk Valley and connects the eastern margin of the Catskills.

Viewing the little folded and the much folded sections of the valley with respect to the rigidity of their respective strata, it is particularly clear that the thin Ordovician section supported by massive Precambrian

rocks yielded little, while the thick section of the strata bore the brunt of the shortening. It is, therefore, to the presence of the massive basement that the unfolded areas of Canada and New York owe their character, and the basement acting as a buttress received the thrust, protected the overlying sediments, and compelled condensation by folding in the narrow zone of thick sediments just to the east of it.

Applying this criterion in Pennsylvania, Maryland, and West Virginia, the stratigraphic section is seen to consist at the base mainly of rigid rocks, while the weak rocks form the top of the section. These lower massive rocks would unite with the Precambrian basement in forming an efficient buttress.

From central Virginia down to the end of the Appalachians the closely folded rocks of the valley include beds from the Pennsylvanian to the top of the Lower Cambrian. These Lower and Middle Cambrian beds (Rome formation at the northwest and Watauga shale at the southeast) present many facts which indicate a derivation from the northwest, just as was the case for the Lower Cambrian beds in New York and Vermont. Doubtless the same explanation holds both at the north and south—that is, that the Precambrian floor rose rather rapidly westward—so that the lower sediments overlapped on it until only those of Ordovician and Upper Cambrian age remain resting on the Precambrian. A reasonable reconstruction of the Ozark dome brings its southeast margin along the Mississippi River, about 200 miles from the close folds of the Appalachians. In the Ozark dome only Upper Cambrian is present, so that somewhere in central Tennessee lies the west edge of the Lower Cambrian beds and the probable margin of the Precambrian rocks of the land. While no more than a probability can be established in the southern Appalachians of a connection between the Precambrian basement and the little folded areas, that relation can be asserted as definite for the northern half of the system. The correspondence of types of folding at the north and south is so close as to warrant adopting the same explanation—that is, a continuous Precambrian plateau underlying the present Appalachian Plateau and forming a great buttress which confined the extreme folding into a narrow trough on the southeast wherein lay the heavy Cambrian deposits.

PALEOZOIC GEOSYNCLINES

It is to be noted that this Lower Cambrian trough with its excessively folded beds does not coincide with the deep part of the Appalachian synclinorium under the plateaus. The latter has generally been taken as roughly the situation of the Appalachian geosyncline, if the Paleozoic

section is taken as a whole. Not much is known of the northern extension of the geosyncline. As far as higher beds are concerned, it appears to pass through the heavy Devonian sediments of the Catskills and along the Ordovician of the Hudson Valley. This synclinorium is not as deep as that which lies east of the Green Mountains, however, which contains Silurian and Devonian strata as well as Ordovician and Cambrian. In Tennessee the thick Paleozoic sections of the east side of the Appalachian Valley include a full section as high as the Mississippian. The Pennsylvanian beds only come to the west side of the valley, so that the position of the Paleozoic geosyncline is probably in the closely folded valley. In Alabama the thickest Mississippian and Pennsylvanian sections are extended well toward the east side of the close folds of the valley. Midway of the system the thick sections of Pennsylvania and Virginia lie in the middle of the closely folded belt. Thus, to sum up, in the system as a whole the Paleozoic geosynclines and the closely folded belt of strata correspond closely, although in the central Appalachians the geosyncline appears to lie farther west than it does either at the north or south.

When the geosynclines are separated according to geologic systems, important relations appear which the generalized Paleozoic section does not bring out. These may best be described in terms of the major Blue Ridge-Green Mountain anticlinorium. The Algonkian geosyncline lies almost wholly to the east of that uplift, on which are exposed older and deeper rocks. In northern Vermont and Canada the geosyncline also extended somewhat to the west of the Green Mountain axis. The Lower Cambrian geosyncline had the same general position as that of Algonkian time, but its western margin lay farther west, from 20 to 80 miles beyond the Blue Ridge arch. In Upper Cambrian time this plan was reversed, and the geosyncline extended far to the west of the folded zone, its eastern border being near the Blue Ridge arch. This general arrangement held for the later Paleozoic sediments, with the eastern border of the seas only occasionally extending east of the Blue Ridge line. After the Paleozoic, deposition began again east of the Blue Ridge and has there remained.

It is of dominant interest in these relations that the heavy deposits of the Algonkian and Paleozoic geosynclines overlap each other and form a maximum total section where now are situated the Blue Ridge arch and the Appalachian Valley. Thus, in general, the highest piling up on folds and faults coincides with the thickest masses of strata. This fact, together with the double reversal in position of land and sea, is of crucial importance to the theory of isostasy.

MAJOR LINEAR FOLDS

As has been already stated, previous discussions of the Appalachians have been confined to the closely folded belt; little was said of the gently folded rocks except that the Appalachian folds die out northwestward; only cursory mention has been given to the rocks underlying the Paleozoic. In order to know the Appalachians in full, however, it is necessary to consider all the territory from the Atlantic Coastal Plain to and even beyond the Mississippi. A brief presentation was made in 1914 by the author of the results of such analysis for the folded belt and the older rocks lying southeast of it. The results of a similar analysis, not only of the folded rocks but of the gently flexed area of the Mississippi Valley and Great Lakes district, are presented herewith in plate 4. The synclinal and anticlinal axes shown thereon are, of course, generalized and locally compounded of a number of minor folds. The simple process was followed of plotting on the map the highest part of each anticline and the lowest part of each syncline, which was in fact the only thing to do. In this work there were used an enormous number of maps and reports, in the preparation of which most American geologists have had a hand at some place.

Some of the major structural features were described long ago, such, for instance, as the Cincinnati arch, Nashville dome, the Ozark uplift, the Wisconsin dome, the West Virginia coal basin, and the Michigan and Illinois coal basins. The Cincinnati arch has been assigned a variety of directions, usually trending between the east and southeast. This states part of the truth, but omits the intersecting anticline which parallels the Appalachian folds. This connects the Nashville dome in Tennessee with the Cincinnati arch, separates the Appalachian coal basin from that of western Kentucky and Illinois, separates the Michigan from the Appalachian coal basin, and thence runs northward into the Ontario projection of the Precambrian of the Canadian shield. The Appalachian coal basin is well known from Alabama to New York and often described. The northern extension of the fold through New York is equally clear, and it parallels with great closeness the anticline of the Blue Ridge and Green Mountains, which is the chief anticline of the Appalachians. It also parallels the major anticline of the closely folded belt west of the Blue Ridge. This great anticline formed one element of the Adirondack dome and raised a belt of Cambrian across the Saint Lawrence Valley. Southward it brought the Adirondacks close to the Catskills and has shown an excess of uplift through most of the Paleozoic. It is traceable always as a major fold practically to the end of the Appalachians in

Alabama. The anticline which passes through the Ozark and Wisconsin domes almost severs the Illinois coal basin from the great basin of Iowa, Missouri, and Kansas.

CROSS-STRUCTURES

The structures heretofore considered are those which run for great distances parallel to the trend of the range and which are so strongly dominant that they have received practically all of the attention given to Appalachian structure. These by no means, however, include all of the Appalachian structures. Folds rise and pitch along their axes, forming saddles and peaks; they curve and they die down. Such structures were well brought out by the early surveys of Pennsylvania and Virginia, where the phenomena are most striking. These were regarded as purely local, however, and no special significance was attached to them. No attention seems to have been paid to the numerous diversions from the normal structural trend. Some years ago the author read a paper before the Philosophical Society of Washington which showed by diagrams that there was a system in these structures and that there were certain lines across the general trend on which anticlines tended to be higher or synclines lower. These were called cross-folds. Certain other lines or narrow zones called cross-warps were characterized by the swerving of many axial lines out of the normal in the same direction. The author was advised not to publish this, however, because it seemed too revolutionary. At later dates, in various folios of the United States Geological Survey, the author has described instances of these structures, and a general affirmation of them as a system was made in 1914 in the writer's presidential address to the Geological Society of Washington.

These cross-warps are exhibited on a very large scale, and in this discussion are called salients and recesses. Cross-warps on a much smaller scale are numerous and decided. A particular striking one crosses East Tennessee just north of Knoxville and passes into North Carolina. Its effects are plainly visible in all of the rocks from Kentucky into North Carolina, including the gently folded strata of the coal basin, the highly tilted beds of the Ordovician and Cambrian of the Appalachian Valley and Mountains, and the schists and gneisses of the Precambrian. This local cross-warp springs from the North Carolina salient and is associated with a great block of the earth's crust, 70 miles long, which has been visibly thrust northwest 8 or 10 miles on the Pine Mountain fault of Kentucky and Tennessee. This fault has the usual northeast trend except at its ends, where it swerves abruptly to the southeast. The southwestern swerve was mapped and described in the author's Briceville folio,

United States Geological Survey, and the northeastern swerve has recently been described by Wentworth as the Cumberland thrust block. Northwest of this thrust block the main axis of the Carboniferous syncline is pushed northwestward out of the usual trend. Along the northeast margin of this thrust block various structures swerve out of the usual trend into nearly east-west courses, although the swerving is not as prominent at this end of the block as it is at the southwest end. The facts summed up show that this excess northwestward motion was shared by all of the rocks from the Pennsylvanian down into the Archean.

A similar local cross-warp is seen in northern Vermont, north of the latitude of Rutland, where all of the structures run decidedly west of north. The Appalachian Valley is here at its highest and narrowest point, so that the youngest known beds to be involved are Middle Ordovician. These beds, the Cambrian strata, and the gneisses and schists of the Precambrian are alike turned aside from their normal courses. This cross-warping runs a little north of west and is part of the general Vermont salient.

In addition to the cross-warps and cross-folds of the Appalachians there are cross-zones along which the pitch of most structures is increased. These are of similar nature with the cross-folds, but the pitch is continuous in the same direction instead of being in two directions as in the folds. A notable example of this feature crosses the Appalachians in New York along the Mohawk River and causes the rise of the Precambrian Adirondack mass from the Paleozoic beds of the Catskills and Allegheny Plateau. The same zone of cross-dip causes a sharp deepening of the Appalachian troughs east of Albany and in northwestern Massachusetts; it also brings down the Devonian beds at Bernardston, Massachusetts, on the Connecticut, and in northeastern Massachusetts it deepens several synclines of Carboniferous phyllite. In the areas between these synclines beds of Ordovician, Cambrian, and Precambrian age are affected.

A similar zone of cross-dips is seen in northern Alabama, extending nearly east and west across the State. These dips, which with reference to the general system constitute a pitch of the folds, are readily visible to the eye in many places. The pitch causes a westward extension and general deepening of the Pennsylvanian coal measures in Alabama, and it is exhibited in the pitch of the entire Paleozoic folded series southward beneath the Cambrian along the Rome fault in Alabama and adjoining northwest Georgia.

CROSS-FOLD SYSTEM

On those folds which distinctly parallel the sharp Appalachian folds and show plainly the same salients and recesses, there are high places and low places. For instance, the low place between Cincinnati and Nashville domes is the direct continuation eastward of the Illinois coal basin and joins a very deep portion of the Appalachian coal basin. Similarly the sag in northern Ohio between the Cincinnati dome and the Ordovician uplift at the west end of Lake Ontario lies directly between the Appalachian coal basin in its deepest part in West Virginia and the Michigan coal basin; thence northwestward it passes through the Cambrian depression of Lake Superior. Where this axis crosses the strong folds of the Appalachians it coincides with the Virginia recess and with a major depression of the Appalachian axis.

The cross-anticline of the Adirondacks is very plain as far east as Connecticut River; westward it forms a barrier between the Saint Lawrence Valley and the Great Lakes and passes northwestward into the area of uplift immediately north of the Great Lakes. Parallel to this a similar major syncline crosses the Appalachian folds of northern Vermont and New Hampshire and forms the upper Saint Lawrence Valley between Montreal and Ottawa. Northwestward it extends up the valley of Ottawa River, marked by numerous inliers of Paleozoic rocks in the Precambrian, and passes into the great basin of Hudson Bay. A part of this system of great cross-folds is the uplift connecting the Ozark dome of Missouri with the Nashville dome of Tennessee. The influence of this cross-fold is readily seen in the general altitude of the close Appalachian folds in northwest Georgia. West of the culmination of the Ozark dome the arch appears to divide, the principal portion running nearly west through Missouri and into eastern Kansas.

The most southerly of the cross-synclines is much concealed by the young deposits of the Mississippi embayment. It causes the great deepening and expansion of Pennsylvanian rocks in central Alabama near the Cretaceous cover and is exhibited in the great Pennsylvanian synclinatorium of Arkansas River in Arkansas and Oklahoma. Parallel to and south of this a belt of major uplift in Arkansas and Oklahoma connects the Ouachita, Arbuckle, and the Wichita Mountains. South of this belt other folds, probably of the same system, are exhibited in Texas and Louisiana. Detailed information about these is scanty, however, and is derived mainly from drill records.

SOUTHWARD CONVERGENCE

Attention has already been called to the parallelism of the close Appalachian folds and of the major syncline of the Appalachian coal field. This parallelism is so phenomenal as to deserve strong emphasis. Not only do the major folds rise and fall in unison, but they swerve from the general trend in the same way and along the same cross-lines. The parallelism is not perfect, however, and the axis of the Appalachian coal basin converges in Kentucky and Tennessee with the stronger eastern folds. This was the result of the excess advance of the Cumberland thrust block in front of the North Carolina salient. West of the coal basin synclinorium the other major axes also converge southward; these include the Nashville-Cincinnati anticline, the Michigan-Illinois syncline, and the Ozark-Wisconsin anticline.

NORTHWARD THRUST FROM LLANORIA

This convergence of axes appears to be the result of two factors: (1) the excess northwestward advance before the North Carolina salient, and (2) a similar but slight northeastward advance of the Ozark mass. The latter advance seems to have been the result of pressure delivered by the landmass of Llanoria northward through the Ouachita uplift and the Arkansas synclinorium against the borders of the Ozarks. Evidence of this northward shoving is seen in the overturning of the folds toward the north in Arkansas and eastern Oklahoma and in a similar though slight overturning with faulting around the north of the Ozark dome. The latter zone of steeper northward dips extends eastward into Kentucky, where it is complicated by an east-west zone of faulting.

The northward compression evidenced in the Ouachita and Ozark region might be equally plain in the Appalachians were it not masked by the greater thrust from the southeast. The general pressure and northward motion of the crust, so plain in the Ouachitas, is part of the general system underlying similar structures throughout eastern North America. It is even traceable dimly under the Cretaceous cover by means of drill records. It is a curious fact that a section running east of north from the Ouachita Mountains through the Ozark uplift to northern Illinois is almost a duplicate of a section running at right angles to it from northwest Georgia through the Nashville dome to northern Illinois. The chief structural difference is that the Ozark dome is slightly higher than the Nashville dome, so that the Precambrian is exposed.

RELATION OF CROSS-FOLDS TO SALIENTS

The general plan of the axes of eastern North America clearly exhibits two systems—one due to folding in the major Appalachian direction with trends from southwest to northeast, and the other substantially at right angles to this trend. The plan of the axes further exhibits a major relation to the deforming force of the Appalachians, in that the principal cross-anticlines extend northwest from the principal salients in Vermont and North Carolina, where the horizontal pressure and motion have been the greatest. Thus, from the Vermont salient the cross-anticline extends northwestward through the Adirondack uplift, cuts off the Ontario trough from the Saint Lawrence trough, and goes to and through the uplift between the basins of Lake Superior and Hudson Bay. From the North Carolina salient (the greatest of all) there extend the Nashville-Ozark cross-anticline and the Cincinnati-Wisconsin cross-anticline. Between these major cross-anticlines lies the great synclorium of the Illinois coal basin, which passes southeastward into a minor recess in the North Carolina salient. Similarly, the Arkansas synclorium and the central Alabama coal basin line up with the recess of central Alabama. Also, the cross-syncline through the Lake Superior basin, the Michigan basin, and the deep West Virginia coal basin passes directly into the Virginia recess. A considerable syncline extends northwestward from the New York recess through Pennsylvania, but dies out in western New York. The great recess of the Gulf of Saint Lawrence is occupied, so far as can be determined, largely by Carboniferous beds in a great syncline. It is thus seen that the major salients and recesses of the folded Appalachians, which are the expression of greater or less horizontal advance, are directly connected with the major cross-folds of the plateaus and the Mississippi Valley. Their community of nature is shown by the fact that the salients of maximum thrust are continued in the cross-anticlines, where uplift is most, while the recesses of minimum advance are continued in the cross-synclines, where uplift is least. From such relations the conclusion can hardly be avoided that one cause is to be assigned to them all. These relations are shown on the map, plate 4.

AGE OF AXES SHOWN

In tracing the numerous axes shown on the map the endeavor has been made to show only those which were formed at the close of the Carboniferous. Axes of other ages have been determined, but this has usually been possible only where they diverge considerably from the axes of Carboniferous age. The Adirondack axis, for instance, existed to some

extent from the Precambrian up to the Devonian. In the northern Ozarks there were Devonian axes in considerably different position from those of Carboniferous age. In northern Illinois there is considerable discordance between axes of the two ages; the principal north-south Devonian uplift passes directly into the synclinorium of the Illinois coal field. It is to be observed in connection with these discrepancies that they involve no great difference of dip and little shortening.

It is not always possible to determine the precise age of individual folds where Carboniferous rocks are not involved in them. In making such determinations this principle has been followed; if a fold in the Carboniferous rocks extends directly into a similar fold of the underlying rocks so that both form consistent parts of a whole, it is considered that the fold in the older rocks also is of Carboniferous age. While this method may occasionally lead to mistakes, it is believed to be sound on the whole. The fact that the axes worked out in this way form a consistent plan is the best proof that the procedure is correct.

PERIODS OF FOLDING

The subject of this discussion is naturally the deformation at the end of the Paleozoic which produced the special characters of the Appalachian system. Deformation of the Appalachian rocks was by no means limited to that period, however, but took place at various times before, during, and after the Paleozoic. None of these upheavals, however, compare in intensity and geographic range with that which ended the Paleozoic except the movements which closed the Triassic. The latter deformation was of a totally different kind from that of the Appalachian revolution.

The various earth movements fall into two classes whose results differ enormously. First, because most common, are the broad epeirogenic uplifts which caused oscillations of the crust with slight domes and basins. These movements are recorded by overlap and hiatus in deposits, without noticeable differences of dip. Such movements took place at a great number of epochs recorded in the strata of the Paleozoic, Triassic, Cretaceous, Tertiary, and Quaternary periods, and are doubtless going on at the present day.

The second class consists of the horizontal movements of the crust, which folded the rocks laterally and pushed them up into long, high arches separated by narrow troughs. The chief of these movements closed the Paleozoic and is called the Appalachian revolution; it consisted of a double movement in Carboniferous time, the second being far the greater of the two. A similar movement took place in eastern New

England and Canada in the late Devonian and early Carboniferous, but it was much weaker and limited in area.

Between these two major kinds of deformation there are many of intermediate nature. A few of the vertical movements were concentrated here and there enough to produce actual and visible folds. Such movements took place in the Lower Ordovician of Tennessee, Georgia, and Alabama, and at a similar period in Pennsylvania, New York, Vermont, and eastern Canada. Between the Ordovician and Silurian a slight movement of this nature took place in a small part of southeastern New York and in southeastern Maine. This has been called the Taconic revolution, but it is too unimportant for such a designation, and it is not exhibited in the Taconic Range. In these there was a small element of horizontal movement. In many of the other vertical movements it is difficult to determine whether or not the crust moved laterally. In addition to general upward movements there were those of tilting, during which erosion quickened and the seas and their sediments expanded enormously. A major movement of this kind took place late in the Cambrian, spread Paleozoic sediments for the first time over the interior of the continent, and raised Appalachia east of the interior sea. This was the real beginning of the Appalachian system. All of these kinds of deformation have acted on the Appalachian region and have united in a record of great complexity.

The Appalachian region has been affected by strong deformation since the Appalachian revolution. Mention has already been made of the Triassic dislocations and their general accordance with those of the Appalachian system. As has been stated, the trends of the Triassic structures exhibit just such broad curves as are so plain in the Appalachian folds. The Triassic structures, however, strike somewhat more nearly north and south than the Appalachian structure, in common with similar trends in the Precambrian structures. In North Carolina the Triassic structures are only seen in the eastern part of the Appalachian area where it is broadest. Passing northward through Virginia the Triassic basins transgress slowly westward on the Appalachian folds until in southeastern Pennsylvania they have crossed the Blue Ridge axis into the Great Valley. Thence northeastward they recede somewhat from the valley belt of folded rocks, but continue in or just east of it in the Hudson and Champlain valleys of New York. East of these valleys the Triassic structures are well developed in Connecticut and Massachusetts and continue up the Connecticut Valley in Vermont.

The broad structural units of that time consist of three great blocks of the crust, the central one 80 or more miles wide from east to west. This

central block was itself gently arched and faulted at many places, especially at its borders, where it was relatively lowered one or two miles by marginal faults. The Triassic deformation shown in normal faults and tilted blocks involved a slight extension of the earth's crust, thus indicating that the great compression of the Appalachian movement was entirely satisfied and its causes removed. The visible movements of this deformation were almost wholly vertical, and in explaining them it is most reasonable to postulate a simple vertical force.

While it is not intended to discuss here the Triassic deformation, it is important to state that Triassic normal faults have caused serious errors in interpreting the structure where they have cut the older rocks at a distance from the Triassic basins. This is particularly the case in western New England and eastern New York and is one of the factors which entered into the Taconic controversy. The normal faults produced relations just the opposite of the Appalachian thrust faults, and the result of a failure to observe them can be readily understood. Little or no attention has been paid by geologists to these faults in the Appalachians, probably for the reason that few of them are found northwest of the Blue Ridge, where studies of the Appalachians were focused.

The Appalachian region as a whole was also deformed slightly by Cretaceous, Tertiary, and later uplifts. These have taken the form of a general bowing up of two great areas—one coinciding in general with the most folded part of the Appalachians and another roughly parallel area running through Texas, Oklahoma, Missouri, and the upper Mississippi basin. Between these uplifted areas lies the Mississippian embayment, in which the Tertiary and Cretaceous rocks are only partly raised above sealevel. The changes of attitude caused by these folds are very slight and only visible when large areas are considered. Exceptions to this statement are seen in certain definite belts of faulting in Texas and Arkansas, where there are normal faults of considerable throw. As a rule, however, the Cretaceous and later displacements are very gentle warps and are of the same character as the many warps which affected the Appalachian region in Paleozoic time. There appears to be no element of compression associated with them, a fact which puts them into a class quite distinct from the Appalachian structures.

One great fact stands out from the distribution of these movements in time and space, and that is that the Appalachian system, and especially its most folded part, represents a weak belt of the earth's crust in strong contrast with the Canadian shield and the plateau region of the Mississippi Valley. It has been deformed again and again from Precambrian

time down to the present. The principal movements are given in the following list:

Archean: Intrusion of batholiths; folding.

Late Algonkian: Intrusion of batholiths; lava extrusions; eastward tilting in Appalachian region.

Lower Cambrian: Deposition in Appalachian region.

Upper Cambrian: Westward tilting; submergence of eastern United States.

Early Ordovician: Westward tilting; slight local folding in New England, Tennessee, and Alabama. Uplift of Llanoria; Ouachita geosyncline deepened.

Late Ordovician: Westward tilting of Appalachian region; slight local folding in southeastern New York, New Jersey, Maine, and New Brunswick.

Late Devonian: Intrusion of granite batholiths in New England and New Brunswick; lava extrusions and folding in Maine and New Brunswick. Slight folding and tilting in Illinois; uplift of south part of Ozark dome.

Mississippian (late): Uplift of Ozark dome. Strong tilting, perhaps folding, in Llanoria with volcanic activity.

Late Pennsylvanian: Strong folding in Arkansas and Oklahoma.

Permian: Appalachian revolution; intrusion of granite batholiths.

AMOUNT OF FOLDING

The characters in which the Appalachian system differs most from the rest of North America are its linear aspect and the intensity with which the rocks of the crust have been folded and piled up on themselves. The amount of compression and shortening of the earth's crust thus made evident is very great and has always been recognized as of great importance in the consideration of mountain-building. Many estimates have been made of the total amount of this shortening in a northwest-southeast direction. All of them have been seriously underestimated because only the folded Paleozoic strata were considered; some of the estimates have been insufficient even for these rocks, because they have been made in regions where the shortening was least and was satisfied by open folds with few or no faults.

Estimates made by the author show a shortening of 30 to 60 per cent of the original width of the folded belt. In all these estimates a geometrical restoration was made, the folds being given the minimum possible height and the faults the least possible throw. For the Paleozoic

strata the problem was comparatively simple, but for the Precambrian is far more difficult. Folds in the sedimentary gneisses and schists can be determined fairly well, but in the granites and other plutonic or massive rocks dislocation took place only slightly by folding and mainly by a multitude of shear planes on which slipping was possible. The amount of motion on such planes can be determined only here and there where the alteration of original forms, such as pebbles and phenocrysts, could be observed. Wherever these measures were possible the deformation was found to be uniformly great, and original pebbles, etcetera, were drawn out to lengths from two to ten times the original. Furthermore, the general mashing and sheeting of plutonic rocks is abundant evidence that they have suffered enormous compression and shortening. In the sedimentary rocks a shortening of 50 per cent is common in folds of all sizes from those of microscopic dimensions up to those a mile across. In fact, the general order of magnitude of the shortening wherever determinable seems to be in the vicinity of 50 per cent. The shortening diminishes northwestward and is greater in the north and south portions of the system where faulting is more prominent. Taken as a whole, therefore, an estimate of 40 per cent as the average shortening of the Appalachians seems conservative.

The visible width of the strongly folded belt is now 270 miles in the Tennessee-Carolina cross-section and in the Maine-New Brunswick cross-section. In the Carolina section Paleozoic beds are now found in a belt 125 miles wide; in Virginia the belt is of the same width. In the Massachusetts-New York section it is a little wider, while in the Maine section the Paleozoics are found in the whole 270-mile width of the system. This figure does not take into account the southeastward extensions of the Paleozoic into Nova Scotia. It is likely that further detailed information in Georgia and the Carolinas will extend the width of the known Paleozoic belt still farther southeastward.

If, therefore, the Appalachians as a whole were shortened 40 per cent in a northwest-southeast direction, it is evident that the present visible width of 270 miles, plus 30 miles for probable extension under the Cretaceous, represents an original width of 500 miles and that the amount of shortening of the crust is thus 200 miles. This amount is more than three times as great as any previously stated, but it is believed by the author to be a conservative measure. Previous estimates of 40 to 60 miles of shortening for the Appalachians, of 40 miles for the Rocky Mountains, and of 75 miles for the Alps indicate clearly the magnitude of the movements in the Appalachians. It is obvious that this great amount of shortening makes heavy demands on certain theories of

mountain-building which were rather severely strained by the previous much smaller figures. Consideration of such matters will be taken up on later pages.

INFERENCES

DIRECTION OF THE DEFORMING FORCE

From the foregoing analysis of the Appalachians it is clear, as has always been understood, that the narrowing of the folded belt was in the northwest-southeast direction. While it has been generally accepted that the portion of the crust which moved actually went in a northwesterly direction, there is by no means agreement on this point. It is, of course, agreed that the mass southeast of the Appalachian Valley moved northwestward relatively to the little folded area of the plateaus. It is urged, however, by some geologists that while this is true in a relative way it is because the great mass of the crust underlying the plateaus moved southeastward and under the closely folded area, pushing up the folds.

From the standpoint of physics, there is no question but that when there is shortening under strain the part which moves rides outward and upward on the part which is passive. In other words, relief from pressure is not inward toward the center of the mass but outward toward its exterior. It is for this very reason that folded mountain ranges stand high. That this is not only theoretically true but actually so, all experiments which have been performed to simulate mountain folding give perfectly clear evidence. As early as 1860 the English geologists Hall and Lyell made experiments which showed this. In a more elaborate way Willis in 1887 experimented with models intended to copy Appalachian conditions rather closely. In each of Willis' models anticlines rose, lifted a heavy load, then overturned and produced faults, but in no case were synclines deepened. The experiments performed by Adams in 1905 produced similar results. The cylinders of marble which he compressed endwise within steel jackets expanded outward on planes of shear, forming around each cylinder a bulge which was in reality an anticline.

The relations which were deduced from theory and corroborated by experiments are readily to be seen in the finished facts of nature. The principle is, as has already been noted, that the folds and thrusts are largely supported and controlled by competent or rigid beds. Thousands of instances of this are observable on every possible scale. It can not be gainsaid that a rigid bed will thrust itself into weak, pliable strata; but how can the reverse be done? One instance may be given which makes the point clear. In northeastern Tennessee and adjoining parts of North

Carolina there is a great overthrust fault whose horizontal movement is visibly from 10 to 20 miles. The plane itself can be followed beginning at the west in the Middle Ordovician and passing eastward and downward through thousands of feet of Ordovician and Cambrian deep into the Precambrian granites. In places the overthrust mass composed of massive Cambrian quartzites rests on weak Ordovician shales; in other places massive Precambrian granite, mashed into horizontal layers by shear planes, rests on the edges of vertical Cambrian shales and limestones. The weak beds are scarcely even slaty, while the massive granites have been mashed and sheared. Having in view the relative behavior of the pliable and the massive beds, which follows a universal rule in the Appalachians, it seems impossible that the weak Ordovician shales should have forced themselves downward into regions of greater strain and pushed aside the massive Cambrian quartzites. It is even more incredible that the weak Cambrian shales should have thrust aside the massive granite and burrowed beneath it. Even if such an attempt should be made the enormous difference in relative strength of the two rocks would have prohibited any downward motion on the part of the shales.

An instance of this on a large scale is the great Cumberland thrust block already alluded to, in which the massive Carboniferous Lee conglomerate, 1,200 feet thick, has been pushed far northwestward up and over the shales and sandstones of the Pennsylvanian and Silurian for at least 10 miles. On a still larger scale the excess compression and uplift at each of the three great salients of the Appalachian gives testimony to the same thing. It is not mechanically possible that the shales and sandstones of the Carboniferous should have underthrust the older, massive sediments and granites and raised masses of them covering thousands of square miles.

Another line of evidence on this point is the depth of the major synclines. If the folds were raised by underthrusting, then the synclines were the active factors while the anticlines were passive. As already explained, the principal synclines are roughly of the same depth with reference to sealevel. Departures from this, however, are in the opposite direction from what would be expected if the plateau masses were underthrust against the folded mass. The eastern of the great synclines are higher in relation to sealevel than the western ones, instead of being lower, as the underthrusting theory would require. This general arrangement of depths, however, is precisely in accord with the idea of overthrust from the southeast.

The general distribution of intensities of deformation furnishes strong evidence on the direction of the movement. Folds, faults, and meta-

morphism increase in number and strength toward the southeast. If the plateau mass were underthrust against the faulted mass, the reverse should be true, and the greatest intensity of all these structures should be along the southeast margin of the plateaus, where the advancing mass under the plateaus was thrust against the belt of sharp folds. In this situation, as has been described, the Paleozoic sea-floor slopes upward toward the west. The scene was therefore set for a maximum localization of strain and therefore of its effects along this line. Southeastward the effects of the pressure should be distributed and diminished, if underthrusting were the real process. As has already been stated, there is a sharp change in the amount of deformation in that situation, but there is by no means a maximum there. Metamorphism, an evidence of maximum pressure, is not exhibited there at all. It is not noticeable for 30 or more miles to the southeast, and it increases definitely away from the plateaus. Nor do the folds and faults decrease eastward. The few exceptions to this rule are due to local changes in the stratigraphic column and hardly form one per cent of the whole. Therefore, on the principle that where the maximum pressure is applied there the maximum results should be found and should diminish at a distance, the case is plainly against the theory of underthrust on the northwest and for the theory of overthrust from the southeast.

HOW THE DEFORMING FORCE WAS TRANSMITTED

Deformation of the strata has proceeded to various degrees of completion in the Appalachians. In the slightly deformed beds it is possible to assign a variety of modes of operation of the folding. In the deformation of moderate intensity, such as the open folds of the Great Valley, it is obvious that the massive strata, like dolomite and quartzite, have carried the brunt of the load and transmitted the strain from one area to another, while the weak shales and thin limestones have failed. In the areas of maximum deformation at the southeast of the range only those rocks of the greatest strength have preserved their form to any extent, and in many places even these have been sheared and mashed by the strain until they can scarcely be recognized, as, for instance, a fine muscovite schist derived from the granite. In all of the phenomena one fact stands out—that is, that the weak beds have had little part in transmitting the deforming force and that the rigid beds transmitted the most of it until they were overcome in succession by the eastward increase of the forces. Each mass, whatever its rigidity, had to be sufficient unto itself or it failed. This was on account of the lack of cohesion

between the layers through the original sedimentary partings. Free movement of one layer on another is clear in any section of closely folded rocks, and indeed there could have been no other result unless the layers were stretched apart or piled together. Theoretical considerations, experimental results, and observation establish this principle beyond question. In fact, no one with a natural section of closely folded rocks before him would raise the question.

When this principle is applied to the larger groupings of facts which cannot be taken in with a sweep of the eye, one large feature of distribution is highly important. With respect to rigidity the rocks have substantially the following order: shale, thin limestone, massive limestone, dolomite, sandstone, quartzite, gneiss, granite and other plutonic rocks. In applying this order of strength to the various areas in the Appalachians, it is seen that only in certain areas are large thicknesses of one kind of rock combined in one unit. Instances of such units are the Middle Cambrian shales of East Tennessee and northwest Georgia, a thousand feet thick; the Knox dolomite of East Tennessee and southwest Virginia, over 3,000 feet thick; the Kittatinny limestone of New Jersey and Pennsylvania, 4,000 feet thick; the Lower Cambrian quartzite group of East Tennessee and North Carolina, 2,000 feet thick; the Carboniferous Lee conglomerate of East Tennessee, Kentucky, and Virginia, over 1,000 feet thick; the Lower Cambrian Great Smoky conglomerate of North Carolina and Tennessee, 10,000 feet thick, and the Precambrian granites, diorites, and gneisses of the Appalachian Mountains and the Piedmont. Groups of mixed rocks of alternating hardness, such as shales and sandstones, are seen in the Devonian of New York, Pennsylvania, and Ohio and the Pennsylvanian rocks of all the coal measure basins.

Viewed in a broad way, the stratigraphic column of the Paleozoic beds is strongest at the base in Vermont and Canada and also in East Tennessee and Georgia. It is also almost equally strong at the top of the section of Tennessee and southwest Virginia. Elsewhere in the Appalachians the rigidity of the column is greatest near the base, although less so than in Tennessee and Vermont, while the upper part of the column is markedly weaker. By far the most rigid mass of rocks which is visible, however, is the Precambrian. The resistance of granite to compression is well known both in scientific tests and in natural phenomena. The strength of diorite and other plutonic rocks approaches that of granite, and the Precambrian gneisses also have a relatively high degree of resistance to deformation, their minerals being the same as those of granite and the individual grains being interlocked with each other. The thin seams of mica in the gneisses, and to a greater degree

in the schists, introduce some ease of motion, although not to the same extent as in sedimentary layers because of the interlocking of the mineral grains. The fact that they did yield is obvious wherever the gneisses and granite were brought together in the Appalachian deformation.

Yielding is equally obvious in the Triassic deformation where faults cutting 20,000 feet of strata or more were imposed on the Triassic sediments by the Precambrian granites. Furthermore, it is shown in the numerous synclines of Paleozoic rocks infolded in the Precambrian. On all of these the trend of the Precambrian was imposed, as has been already described. The overwhelming power of the thrust by the Precambrian granites is shown by the fact that the greatest known overthrust in the Appalachians extends visibly down into the granites which formed the overriding mass. Summing up, therefore, it seems clear from theory, from detailed observation, and from a variety of generalizations that the Precambrian granites were the rocks which transmitted the pressure to the Appalachians; that the more massive groups of the Lower Paleozoic sediments transmitted the forces upward and northwestward, and that the weaker beds which constitute the Middle and Upper Paleozoic were comparatively passive.

The conclusions stated in the preceding paragraph appear to account completely for the phenomena of the closely folded belt of the Appalachians. In this belt the element of lateral shortening overshadows that of vertical uplift. The latter, however, is by no means inconsiderable but is to be measured in miles. The uplift as measured by reconstructing the folds is from 5 to 10 miles or more, according to the region selected and to the principles followed in restoring the folds. This amount is to be compared with the 200 miles of lateral shortening already deduced. In view of this great shortening and the piling up which it must have caused, it is seen that from 5 to 10 miles is a conservative estimate of the heights to which the folds would have extended unless eroded.

The proportion of vertical to horizontal motion changes rapidly northwestward and is reversed in the plateau region. In fact, the amount of lateral shortening on the various great domes like the Cincinnati, Nashville, Ozark, and Wisconsin uplifts is measured in thousands of feet. The Cincinnati dome, though often called an arch, has in reality such a slight curvature (one or two degrees from the horizontal) that no known rocks could support themselves on this arch by their own strength. They must, therefore, in this arch and in similar ones, some gentler and some more pronounced, be supported by pressure from below. It is equally clear that horizontal pressure alone could not raise such an arch because

the beds are not competent to stand the strain. Furthermore, no arrangement of pressures can be determined which would focus on a single area from all sides so as to raise a symmetrical dome like the Cincinnati and other domes.

Still less is this possible when several domes are considered—for instance, the Cincinnati, Nashville, and Ozark domes. How is the pressure northward to the Cincinnati dome and southward to the Nashville dome to be derived from the narrow saddle between them? Similarly, how is an eastward pressure against the Cincinnati dome and a southwestward pressure against the Ozarks to be derived from the gentle basin of the Illinois coal measures? It seems necessary to conclude, therefore, that a considerable amount of vertical pressure was applied to raise these domes which could not raise themselves by horizontal pressure, yet these domes and their connecting basins fall so plainly into a system with the Appalachian major structures that we must conclude a community of origin for the respective forces. Where free, however, to assign different proportions to the two major elements of the forces, lateral and vertical, the only requirement in connecting the two kinds of deformation is a suitable means for transmitting the pressure and a suitable cause for localizing it under the respective domes. The medium is attained in the granitic rocks of the Precambrian. Three of the great domes, the Wisconsin, Ozark, and Adirondack domes, exhibit the Precambrian at their cores. The Cincinnati and Nashville domes do not, but there are no other differences, and this one appears to be due to their lesser height and thicker sediments, so that erosion has not yet exposed the granite. The cause of the vertical pressure will be discussed on later pages in connection with that of the horizontal pressure.

The sum total of the Precambrian strength is so vastly greater than that of the Paleozoic beds that the Paleozoics inevitably had to yield when the pressure was applied. The effectiveness of the Precambrian rocks, moreover, was enormously amplified by their great mass which far exceeds that of any rigid unit in the Paleozoic section.

THEORIES AS TO CAUSE OF DEFORMING FORCES

EARLY THEORIES

The beginning of structural geology was made when it was recognized that beds now high above the sea were originally deposited on the sea-floor. A corollary of that concept was that each stratum when deposited approached a horizontal position, just as do the beds now being formed. The departure of the beds from such a position was seen to require the

application of force. The first attempts to explain the great upheaval and tilting of the rocks were simply to call into being for each case a special convulsion of the earth. The various upheavals or systems of folded mountains were seen on closer knowledge to possess many features in common. The recognition of this led to the belief that there was an orderly system in the matter and that all folded mountain ranges and the larger deformations were produced in much the same way, although at different periods. With the introduction of this element of order the acquirement of knowledge of mountain-building became better directed and less speculative. Causes whose nature are unknown were in the main set aside and attention was chiefly focused on connecting with the problem causes which were within the experience of man or could be justly deduced from the facts of observation.

In recent years there are indications of a return to advocacy of causes which can not be determined to exist and which are outside of the realm of human experience. Speculation of this order has its merits, but its drawbacks are also obvious and may become an obstruction rather than a help to progress. The final test of all theories lies in the facts of the field, and any theory fails which does not satisfy that test. The number of theories proposed to explain mountain ranges is large; indeed, it is a tribute to the intelligence or ingenuity of man that so many different conclusions as to cause can be drawn from a given set of facts which appear at the outset to be simple. No attempt can be made to test the theories exhaustively in these pages, and only their major points will be discussed. The wide divergence between the theories shows that the field need not be considered closed to new ones.

The first theory as to the cause of the Appalachian folds was set forth by Rogers, who likened the folds to a set of huge waves, with the implication that they were produced in succession and in a similar manner. This theory really did no more than to call on a special convulsion for them. Later theories were based in part at least on known physical principles and had their merits. They are of two general classes—first, those which depend on forces coming from outside of the earth and, second, those which rest on forces derived from the earth itself.

The theories of the astronomical class have been repeatedly analyzed by mathematicians and astronomers and have been found to possess defects which are serious if not destructive. Such, for instance, is the theory that the moon was originally part of the earth, but parted company from it as a result of a higher rate of revolution than now exists. The other conditions and results of such a separation are such that no credence is given to the theory in connection with mountain-building.

A modification of this theory of higher speed of rotation calls for the slowing down of the speed with a consequent approach to more nearly spherical form. Direct results of this process would be a vast series of folded ranges trending north and south across the equator and also a tremendous stretching of the crust in the vicinity of the poles. Since the crust of the earth shows no such plan, the theory fails to meet the test of facts in geography. Furthermore, it fails to meet the facts in point of time, for such a slowing down of the earth's revolution must have been gradual and its effects to a considerable extent rhythmical. No such rhythm is observable, however, for the greatest deformations of the earth, those of Precambrian, Paleozoic, and Tertiary time, are separated by enormously different intervals.

Another cause assigned is that of variation of the attitude of the earth's axis, with attendant changes in the crust of the spheroid. While variations appear to exist, they are not known to be large, and there is no demonstration, or perhaps even indication, that they affect mountain structure. In short, none of the theories of mountain-building which depend for their causes on factors of an astronomical nature satisfy the facts of geology and the calculations of physicists and astronomers.

Among the various theories which depend in part on facts of observation, the oldest is that of radial contraction of the earth due to cooling. Others are the theory of a tetrahedral form as a result of contraction; the theory of isostatic adjustment between crustal masses of unequal density; the theory of suboceanic spread, in which the suboceanic portions of the crust are thought to be denser than those beneath the continents, which relation causes a flow of the suboceanic mass toward the continents so as to equalize the masses. All of these theories depend on gravity as the moving force.

CONTRACTION

The hypothesis that mountain-folding was caused by shrinkage of the earth on account of loss of heat has been discussed and supported by many eminent geologists. It is based on the fact that the earth radiates heat faster than it receives it from the sun, and on the supposition that there is no other appreciable source of heat. It is in addition based on the theory that the earth has been derived from a nebulous mass through various stages of condensation. The actual attractions of the nebulous particles for each other were finally combined in the solid earth into an effective force called gravity. Since the earth actually loses heat by radiation, it must slowly condense and contract. This change of volume is most rapid at high temperatures, so that the cool outside or crust of

the earth is relatively more fixed in condition than the interior and is wrinkled on the more rapidly condensing interior.

If the continuing loss of heat of the earth without replenishment is granted, there must be condensation and wrinkling of the crust. Grave doubt has been thrown on the fundamental assumption as to loss of heat by the planetesimal hypothesis of Chamberlin, which calls for a steady, though small, accession of meteoric matter that gives on impact some accession of heat. A further serious blow has been dealt to this assumption by the recent discoveries in radioactivity. Long before the theory had to meet these modern doubts, it encountered several major difficulties which were necessary consequences of the theory.

Important among these obstacles is that of periodicity, which has been a stumbling block to many other theories of mountain-building. If mountains were raised by contraction due solely or mainly to loss of heat, then the strains began and increased regularly. Since their relief by deformation was determined by the strength of the rocks, and since this strength can not be considered to have varied from age to age, it follows that the stress should have increased rapidly to a certain point controlled by the rocks themselves and then been satisfied by deformation. Then the process would have begun over again, and a notable periodicity in mountain-building would have certainly followed. There are those who advocate periodicity and rhythm in movements of the earth which were sufficient to produce important changes in the distribution of the sea and its animals, now recognizable in terms of era and system. There is no demonstration, however, that the various eras are of equal length or separated by equal movements. Far less is it the fact that the great mountain-building movements like that of the Appalachians are separated by equal periods or were of equal intensity. The tremendous difference in intervals and energy between the Devonian and Permian movements in the Appalachians is proof that they were not equal. In this general respect the theory fails.

A deficiency of this theory, which is perhaps the principal one, is of a quantitative nature. In order that the folded mountain ranges may have been produced as the result of contraction, the radial movements must have been translated into horizontal movements of the crust. Many mathematical calculations have been made as to the time needed for contraction through loss of heat to produce the observed horizontal movements in a given mountain range. These calculations have been based on such estimates of horizontal shortening as 40 miles for the Appalachians and 75 miles for the Alps. Even on the basis of such shortening it has been recognized by geologists that the strain put on the theory

to satisfy such motion was very great, if not too great. Since, however, as has been shown on previous pages, single thrusts of 20 miles throw are known in the Appalachians, and thrusts are probable which on a single plane exceed the total contraction previously assigned to the Appalachians, it is evident that the theory has not been fairly tested in a quantitative way. When the theory is confronted with a probable shortening of 200 miles in the Appalachians, a situation results which is certainly serious for the theory. Geometry points out to us very simply that one mile of shrinkage toward the center of the earth will produce 3.14 miles of horizontal shortening, if all the shortening is concentrated into one belt. Thus the shortening visible in the Appalachians requires that the crust shall have shrunk radially 63 miles. No calculations by physicists permit a shrinkage during the Paleozoic that even faintly resembles this, and studies by geologists have found reasonable permanence in the earth, instead of the vast changes that would ensue from such a shrinkage.

While this process may have operated to a slight extent, it clearly is not the principal factor in Appalachian deformation. It should be borne in mind that this test of the theory applies to the deformation at the end of the Paleozoic. The principal deformation preceding that was in the Precambrian, so that only that shrinkage which accumulated during the Paleozoic was concerned in the Appalachian revolution. He would be a bold man indeed who would assert that during Paleozoic time the earth has shrunk 63 miles radially, or even a small fraction of that amount. On the contrary, the dynamic history of the earth during the Paleozoic, as interpreted by a great number of geologists and from many angles, is one of moderate movement, with two exceptions, and only slight modification of the landmasses. The general shape of the continents and the seas remain roughly the same. In meeting the test of Appalachian structure, therefore, the theory of radial shrinkage as a major cause of folding is seen to fail completely.

SUBOCEANIC SPREAD

The theory of suboceanic spread makes the fundamental requirement that beneath the oceans the density is greater than elsewhere, a relation that appears to be supported by a good basis of fact. The test of the validity of the theory is the arrangement of its results with reference to the oceans and the particular nature of the results from place to place. The general arrangement is in accord with the theory, in that great deformations have been and are marginal to the oceans. The detailed facts, however, are not so in accord. The Appalachians, for instance,

under this theory would have been thrust northwestward by spread of the sub-Atlantic crust. As a matter of fact, an important landmass lay to the east of them during the late Paleozoic. On the Pacific border of North America, while the mountain ranges border the ocean in accordance with the theory, their thrust is toward the ocean. Another requirement of this theory is the permanence of the ocean basins, for if the density was originally sufficient under the Atlantic, for instance, to have caused the northwestward thrust of the Appalachians, such density would be expected to continue and could not be shown to have discontinued.

A further deficiency in this theory is a quantitative one. Even if the utmost known differences in density of the crust are granted, a very limited expansion landward in terms of miles is provided. This utterly fails to meet the requirement of 200 miles of horizontal motion in the Appalachians, for the distance from the center of the Atlantic to the Appalachians is not much more than 1,000 miles. The density differences no doubt develop an enormous downward pressure, but the downward motion (and also the lateral motion) is limited by the compressibility of the rocks, which is of an order far different from 200 miles in 1,000. Finally, if this suboceanic spread is to become especially active at the sea margin, the entire mass of the crust must be moved and its strength and its friction overpowered.

Furthermore, this difference of density under the Atlantic must be assumed to have been pre-Paleozoic. Therefore, if deformation were simply a matter of suboceanic weight of solid rock, why did it wait for its action until the end of the Paleozoic era; or, if it were satisfied in the Precambrian deformations, what was left for the Paleozoic revolution? In short, this theory as an explanation of the Appalachians fails to meet the quantitative test of the known distances, times, and physical constants unless another factor is introduced, as in the theory of batholiths.

ISOSTASY

Another theory of the production of mountain ranges has been strongly held by many geologists in recent years. This theory, proposed by Babbage and Herschel more than a century ago, was definitely put forward in 1892 by Dutton, and was supported by many geologists of note. This theory—that of isostasy—supposed that the lands rose because they were made lighter by erosion and that the sea-bottom was depressed by the growing load of sediments. In order that this process should be a continuing and potent cause, Dutton postulated some sort of transfer of the underlying portions of the crust from beneath the oceans to a new place

beneath the land. In his view this lateral transfer was a complete cause for laterally folded mountains.

That such a tendency to lateral transfer exists can not be doubted, but the question arises as to the amount of this transfer. Is it sufficient to cause the great lateral shortening observed in folded mountain ranges? Dutton's theory was deduced largely from his observations in the high plateaus of the west, in which the element of lateral shortening was so slight that the lateral motion due to isostatic adjustment might perhaps have caused the observed geologic relations. The situation, however, is far otherwise in the case of the Appalachians and even of the eastern folded ranges of the Rocky Mountains. In fact, the difficulty of deriving sufficient motion from the differences in gravity due to unloading some thousands of feet from the land have been recognized by most students of the matter as very grave. This is so decidedly the case that most students have considered that, while isostasy may account for the broad, continental, or epeirogenic upswellings, it is inadequate to explain the great folded chains. Dutton's view was exactly the opposite, however, for he concluded that isostasy did account for laterally folded mountains but not for continental uplifts. For the latter movements he found it necessary to postulate an unknown cause, perhaps expansion or contraction of deep-seated bodies of magma. It is important to note that he considered some other factor to be operative in addition to isostasy.

In very recent years there is a revival of this theory and even a decided expansion of it. Bowie in 1920 goes so far as to say that the theory of tangential thrust must be given up in favor of one more modern and more in accord with the facts, and that the mountains resulted from vertical movements due to expansion. He also accepts the existence of other means of deformation than isostasy. The most recent advocates of isostasy claim that its action is complete and that the earth densities are perfectly and continuously compensated. It is not possible to discuss in this paper the mathematical and physical basis of the theory; it has its strong points, but also its weaknesses. It must, however, meet various conditions established by the visible data of geology, and by them must be gauged its success in explaining mountain structures.

Looking at the process of isostasy from the theoretical standpoint, one is led to question whether actual movement did result from these pressures due to differences in load, and, also, if such motion took place, in what part of the crust it would be—in its upper portions or very deeply buried. The probability of actual movement is affected fundamentally by the nature of the materials themselves. If the crust had the fluidity of water, adjustments would be almost instantaneous, and

the high and low spots of the crust would cease to exist. If, however, the rocks had the elasticity of a steel spring, an enormous amount of pressure might be stored up to be later released under favorable conditions. Such movements, however, would be strictly limited by the capacity of rocks to be condensed and later to expand when free. That rocks can be condensed and do expand when free from pressure is well known, and the process has been observed many times in quarries and engineering works. The amount of these motions, however, is very small and is doubtless much less than one per cent of the linear dimensions of the body concerned. The 200 miles of shortening in the Appalachians would thus require more than 20,000 miles of background, if this alone were the cause. It is therefore seen that this process of compression and release does not even begin to account quantitatively for the great lateral movements of the crust.

Another cause appealed to as an agent in support of isostatic adjustment is the increase of heat due to the blanketing of the ocean bottom by the strata and the consequent rise of the isogeotherms and expansion of the bottom. This cause, however, can hardly be considered to favor the process because it diminishes the density of the rock where it operates. Similarly, erosion of the land lowers the surface and is considered to bring the underlying heated beds nearer the surface, thus facilitating expansion and uplift. In this case, too, the rise of isogeotherms would be counteracted by increased loss through radiation. The lowering of the surface might even be so slow that the radiation loss would be sufficient to maintain the position of the isogeotherms. Here, too, the amount of expansion due to increase of heat is a very small matter, even at the surface where expansion is not checked. At depths beneath the surface, however, how can it be said that there will be any expansion due merely to a few degrees of increased temperature? It is more likely that the expansion is potential and is absolutely stopped by the infinitely greater force of gravity. Actual expansion is also definitely limited, for no rock can expand if in so doing it must move other rocks and exert a pressure greater than its own crushing strength.

As was stated above, there can be no doubt of the tendency of the ocean bed to sink under load and of the denuded land to rise. The theory requires that the flow from sea to land be deep-seated, and it obviously does not occur near the surface. Deep-seated flows must, however, encounter the obstacles of friction and rigidity, which inevitably increase downward. The deeper the flow, therefore, the greater is the demand made on the original slight differences of gravity in order that they may really function as a cause. It would seem as though it would require a

very large piling up of sediment before the gravity differences would be great enough to overcome the friction and the strength of the rocks and thus to operate. The actual piles of strata known to us are from 20,000 to 30,000 feet thick at the most. These masses are found only in narrow belts 50 to 100 miles wide near the sea margins. Away from the maxima the totals diminish rapidly and a thickness of one mile might be considered a fair average for the general area of deposition. It must be admitted that this is a small agent for producing the enormous dislocations and transfers of the crust in folded mountains.

It has often been pointed out that the crust is capable of supporting great loads, and it can not be denied that it is strong enough to support large groups of high mountains above the general level. There are two such areas in the Appalachians, each containing about 2,000 cubic miles of matter above the adjoining valleys. The rocks concerned are Precambrian granites, diorites, and gneisses of very high specific gravity, and they pass without change from the mountains down into the adjoining lowland. It is obvious that the earth's crust there sustains large overloads of heavy rock, yet the mountains have not only been carried but have risen no less than 4,000 feet since the Mesozoic. This rise was accomplished in five distinct stages, which indicates that the crust could not only raise and support the load but that it could hold it through five long periods of rest shown by as many successive peneplains. The rigidity of the crust thus shown indicates clearly the order of resistance that must be overcome by the weight of a mile-thick layer of sediment before isostasy can act.

Granted, for the sake of argument, that the initial gravities do differ sufficiently to start the isostatic process, what, then, is to stop it? As the deficiency of mass under the land was supplied by the underflow the land would continue to rise, continue to be worn, sediments would continue to be deposited, and the sea-bottom would continue to descend. This appears to be a process which is necessarily continuous if once started, and it has the advantage of requiring only transfer of and no final loss of matter, of heat, or of any force.

This continuing process, however attractive it may seem, is easily subjected to the test of observed geologic facts. Do the oceans continue to deepen and the land continue to rise or not? The facts of geology emphatically say that they do not. Not only is this process not continuous but it has been repeatedly reversed. Great areas of sea-bottom in the Appalachians and elsewhere have been laid bare and their sediments worn away, even after deposition had been long established. Again and again during the Paleozoic this has occurred. A case of it followed the Silu-

rian, wherein the deep basin filled with Cambrian and Ordovician sediments was raised above the sea and there remained until the latter part of the Devonian. While erosion was going on at the south deposits were still formed in the basin at the north. A similar event took place, but in the opposite direction, when the sediments of the Mississippian were exposed by the rising sea-floor at the north and worn away, only to be again depressed and receive another load of sediments. The maxima of uplift are opposite in the two cases.

The bearing of these movements is this: While the sedimentary basin was actually above land, what started it again on its downward course? Surely not any fresh deposition of sediment, because there was no such deposition until after the depression began. Further, while it was beneath the sea and being loaded more, why should it rise in spite of the added load? During the Pennsylvanian the deposits of the coal measures were laid down in a basin deepening with great steadiness and slowness, as evidenced by the successive beds of coal and their land flora. Why, indeed, should the land have been depressed at all, if isostasy was the cause of uplift of the land? How could deposition have started unless some force had provided a basin?

The most striking case of all was at the beginning of the Upper Cambrian. For untold ages the Precambrian granites and gneisses of half the continent had been eroded from the land and their waste carried eastward into the sea. Then, half of this region sank beneath the sea and a new land, Appalachia, rose from the waves of the east. If isostasy ruled, why did the land and sea reverse their positions? What depressed the land when it had suffered a maximum of erosion, and why did the sea-floor rise in spite of an ever-increasing load? Obviously, not on account of isostasy but in spite of it, for the results are the opposite of those of isostasy. It remains for us to conclude that another cause more potent than isostasy lay at the root of these movements and that its major effects were at times hindered and at times helped by the action of isostasy.

To sum up, there are eight chief obstacles to acceptance of the theory that isostasy caused the folded mountain range: First, isostasy is not in itself an initiating cause, but requires some other force to start its operation. Second, isostasy is a continuing process; therefore it requires some outside force to stop its action; such stoppage is known to have occurred repeatedly. Third, the factors which are appealed to as maintaining isostasy are differences of density and gravity so slight that they can be readily overpowered by other causes; that they were so overpowered is clear from the repeated and vigorous reversals of isostasy

shown by uplift and depression of the crust. Fourth, the existence of peneplains, or surfaces of erosion produced during a long period of quiet on the land, disproves the idea that the land is continually in flux and completely responsive to isostasy. Fifth, the mechanism appealed to for a shift of the vertical force of gravity into horizontal motion is a very deep-seated underflow of rock from sea to land. This is a wholly hypothetical arrangement and must remain so. All that our observation tells us is that lateral folding is most pronounced in the great piles of sediment, which are seldom more than five miles deep and in a few miles of closely underlying granite and gneiss. Sixth, the differences in density brought out by pendulum and plumb-line observations have yet to undergo careful and detailed comparison with the facts of geology. Seventh, the sediments whose transfer initiates isostasy are only thick near the sea margin; their maximum thickness is rarely over five miles and their average is a mile or less for the area of deposition concerned. This load is supposed to overpower the crust and to cause huge transfers of material; in the case of the Appalachians this transfer is of the order of 4,000,000 cubic miles. Eighth, the thick sediments whose weight is supposed to depress the sea-floor and cause the underflow are the very masses which are folded and raised the highest; this is truly an achievement in dynamics.

In the matters just mentioned there is a serious lack of agreement between theory and observation. It is therefore logical to conclude that isostasy is not the cause of folded mountain structure. That conclusion does not, however, deny or even cast doubt on its action in a minor way to reduce and perhaps remove inequalities produced by the action of major forces.

GEOSYNCLINES

It has been said by some writers that the accumulation of sediment in geosynclines was the cause of folded mountain structure. This, however, in so far as the association of folding and geosynclines is true, is merely one step in the line of causation. The thick deposits in the synclines merely serve by their easy folding to localize the deformation. Far back of that lies another cause which produced the geosynclines themselves.

As has been shown, the geosynclines and the strongly folded belt are only coincident in a general way in the Appalachians, and the result in the location of the folded belt would have been practically the same, even if the great mass of Carboniferous deposits in the geosynclines had not been laid down. The geosyncline as shown in the Carboniferous

deposits lies west of the main folded belt, although the latter is commonly understood as the position of the main geosyncline. There is considerable complexity, however, in the position of the geosyncline and it was not the same at all periods. In Algonkian time it lay to the east of the present main uplift of the Appalachians; in Lower Cambrian time it lay slightly farther west, about the middle of the folded belt. In the Upper Cambrian and Ordovician it was still farther west, but it was still in the folded belt. The Silurian, Devonian, and Mississippian geosynclines had about the same position, as stated above, mainly outside of the strongly folded belt.

Thus, the position of the geosyncline progressed westward from Algonkian to late Carboniferous time. After the Appalachian revolution the reverse is true, the Triassic geosyncline lying, for the most part, east of the strongest Appalachian deformation, while the Cretaceous and Tertiary geosynclines were entirely outside of it to the east. Where the thickest deposits of the various geosynclines overlapped and piled up on each other, or, in other words, about where the great Appalachian Valley joins the Appalachian Mountains, there was presented the greatest opportunity for deformation, both in the amount of the sediments and in the position of the rigid Precambrian floor. It is hardly necessary to say that in that position is found the greatest deformation, including the principal anticline of the Appalachians, the great border thrust faults, and the metamorphism of the rocks.

In Algonkian and early Cambrian time the sea lay to the east and land to the west. This was reversed in the Upper Cambrian and was continued through the Lower Paleozoic. In the Upper Cambrian, therefore, there began the rise of land on the east, which was the real beginning of the movements culminating in the Appalachian revolution. A similar but reverse movement took place in the Mesozoic and Tertiary times and appears to be still going on. These major movements—that is, the uplift of the Lower Cambrian geosyncline and the depression of the Lower Cambrian land on the west—have already been mentioned as directly the opposite of the results which would follow from isostasy if that were the only cause. The same is true of the great reverse movement of the Mesozoic and later times which submerged the old land of Appalachia and raised the geosynclines, which had been receiving sediment during most of the Paleozoic.

To sum up, the geosynclines and geanticlines were begun, were increased, and then were reversed in their relative positions, not once but again and again. Thus we are led to nearly the same conclusion for

geosynclines as for isostasy—that is, some greater force caused them and ended them.

The same general relations militate with almost equal force against the theory that geosynclines caused mountain folding, for it is clear that the establishment of a geosyncline in one region was no bar to the shifting of it in later times into different and even distant regions. Nor was it a bar to transformation of a geosyncline of deposition into a landmass. There were, therefore, other forces at work which produced geosynclines, shifted them, and even reversed them. These forces were the ones that finally caused the great folding; their early manifestations were the geosynclines and their associated geanticlines. The geosynclines played their part in mountain-building, however, for their thick deposits gave opportunity for and character to the folding. The depressions of the rigid crust in the geosynclines helped to determine the position of folding, but they were themselves the expression of an already active force.

CONTINUITY RELATIONS

The relations of the various hypotheses to the element of time is most important. The facts of geology determine the relative position in the time scale of the great movements of the crust. These are not continuous but are periodic and separated by unequal intervals; they are not of equal force but they differ as 100 to 1. Presumably, therefore, their causes differ in nature or amount. The forces appealed to for diastrophism are continuous, however, the sole exception being the partition of the moon from the earth, as suggested by some writers. The possibility of partition, as worked out by mathematicians, puts it far back of the Paleozoic, so that it is not a competent cause in post-Paleozoic deformation. Nor could a capture of the moon by the earth, as has also been suggested, account for more than one of the great diastrophisms. It has not yet been suggested that the partition of the moon caused Paleozoic diastrophism and its capture again caused that of the Tertiary.

While the various oscillations during the Paleozoic may be appealed to as evidence of the storing up of forces to be later released, these preliminary movements are wholly out of scale with the final movement. What we should expect from a storing up of such forces as contraction, which is of steady growth, would be rhythmic action with its culminations of roughly the same intensity. This is for the reason that the materials of the crust have not changed their character materially since the beginning of Paleozoic time. Their capacity for storing up strain, therefore, had a definite maximum, and release should have occurred whenever that maximum was reached. It should not have been distributed through.

minor episodes with a tremendous maximum at the end, as was actually the case.

In the element of continuity, therefore, the forces called on and the visible effects differ greatly. The continuity should be apparent not only in time but in space. In regard to space, however, the evidences of diastrophism are far from being uniform or world-wide at any one time. The Tertiary revolution approached that condition, but the preceding ones of the late Paleozoic were distinctly limited and variable. It can not be seriously questioned that the contraction of the earth was greater in the immense period of Paleozoic time than it was in the far shorter Mesozoic, and the same is true for any other continuing cause. Yet the effects attributable to pre-Mesozoic deformation are less widespread than are those of the Tertiary, although we should expect the opposite. Practically all of the theories depend on some continuing factor, like contraction or difference of gravity. They require, therefore, both in time and space, a simple, steady, storing up of strain. This is a continuous process and its release should be rhythmic—a condition which is distinctly opposed by the large facts of mountain-building. This situation indicates, therefore, that there is another factor in the equation which need not be of gradual or steady growth and which operates from time to time with an excess of vigor. What the nature of this cause may be will be discussed on later pages.

CONTINENTAL CREEP

In recent years several theories of mountain-building have been put forward which may be classed as theories of continental creep. They are characterized by the enormous amount of sliding or creeping which they attribute to the continental masses. The first full expression of this sort, although not the earliest mention of it, was made by F. B. Taylor in 1910. He figured the crust of the north half of the earth as having moved southward away from the North Pole for hundreds and even thousands of miles, and stated that this theory was an expansion and modification of the ideas of Suess.

In Suess's theory of 1884-1885 the mountain ranges of Asia, for instance, were considered to have developed around the circumference of a "vortex" or central area in southern Siberia, the oldest ranges being nearest the vortex and the youngest at the outside. Thus the crust was supposed to have moved in general southward in successive sections and at different times. The foundations of his idea were the southward overthrusting visible and the trend lines or arcs of the Asiatic mountains. No explicit statements were made by him about the cause of the pressure

required, the amount of the individual movements, or the thickness of crust affected.

At the same time, 1885, W. B. Taylor promulgated a theory that mountain-folding was due to a slowing down of the earth's rotation. This acted by raising the polar areas to such an extent that gravity pulled the excess matter toward the equator and folded parts of the crust. Since the circumference of the earth at the equator was reduced at the same time, there must have been an east-west compression making north-south mountain ranges. In assigning a cause for the slower rotation, Taylor adopted the idea that the friction of the tides was responsible. The probability of this as a cause had long engaged the attention of astronomers; it had been rejected by Fisher in 1881, and Ferrel had concluded from astronomical observations that there had been no retardation of consequence in a million years. Taylor further calculated that the change in revolution necessary to account for the amount of crustal shortening, which he estimated to be 10 per cent of the original length, would require a former revolution of the earth in four hours. Chamberlin later (1909) arrived at similar conclusions regarding the position and trend of mountain ranges.

According to F. B. Taylor's theory of 1910, the whole crust between the north polar regions and the island loops of the East Indies moved southward as a mass. In Asia the horizontal motion was least in the Himalayas, where the moving crust encountered the buttress of the Indian Plateau, and it was greatest in the East Indies, where motion was unobstructed and is stated to have been in the vicinity of 2,500 miles. The immensity of this transformation was recognized by Taylor, and no cause except one of the highest order—that is, astronomical—could be considered sufficient. Accordingly, he postulated that the earth's revolution was increased, with a tendency to settling of the polar areas and elevation of the equatorial belt.

The mechanism by which this polar change was transmuted into a horizontal motion of 1,000 to 2,500 miles was conceived by Taylor to have been a plane in the earth's crust dipping at a low angle toward the equator; down this plane a part of the crust of the earth was supposed to slide under the influence of gravity. Reyer had already (1888) promulgated a simpler theory of creep, in which he considered that the sediments were folded by a simple sliding down the slope of the ocean basins. The earlier discussion by W. B. Taylor had not gone into the difficulties of the sliding process or the means of accomplishing it. All forms of the theory pass over the element of friction, which must have had a compelling influence. Near the surface of the earth this absolutely stops

motion on planes of any such angle as are contemplated in the theory, while at depths there can not fail to be an increase with the load, whatever may be the modifications of the principle. The difficulty raised by friction is more important in the case of the F. B. Taylor theory, because the assumed plane of motion must pass deep into the more rigid parts of the crust.

The space relations of the F. B. Taylor theory are in reality a chief obstacle to its acceptance, although its author states that it is founded on the trend lines of mountain systems and their space relations, just as was the theory of Suess. The diagram presented by Taylor to show these space relations was drawn on the Mercator projection, which renders it easy to think of unlimited areas north of the continents. From such areas the crust of the earth is indicated in the diagram as having moved southward. In his map of the polar regions, however, drawn on the nearly true scale, this unlimited northern area is seen to be a small affair in comparison with the areas of the continents surrounding it. It is, in fact, hardly larger than the area directly inclosed in only one of the Tertiary mountain loops—that of the East Indies. Since the thickness of the moving crust increases southward, the mass which moved in the East Indies must have been enormously greater than the mass of equal area near the poles. Even assuming that it was no greater, and subtracting from the polar area the mass inclosed in the East Indian loops, nothing is left to satisfy the enormous motions which are postulated for the rest of the world; no source would remain from which such motion could emanate. Granting, for the sake of argument, that the motion did start radially from the poles, a very few miles of motion of all the northern continents would create such a hole in the polar region that the gravity relations would be totally reversed and motion back toward the pole would be compulsory.

While the theory appears to receive strong support from the mountain trend lines, the hypothesis of southward creep of the continents is not the only conclusion that can be drawn from them. Hobbs, on the contrary, concludes precisely the opposite—that is, that the mass of Asia remained stationary, while the suboceanic mass pressed northward against it and was thrust beneath it, raising the mountains around its margin. Taylor states that the crust of the earth moved like a field of ice, crushing against obstacles, such as the Indian Plateau, and flowing past them in sweeping curves. This, however, is only an illustration, and the conditions of the two operations were so different as to leave it little value as an argument. In ice and rock the melting points and

friction are of a totally different order, and even in glaciers a considerable grade is required to initiate motion.

The actual argument from example which can be made for the Tertiary ranges is that of overthrusting. In many places, in Asia, for instance, the thrusting is from the north in accord with Taylor's theory; in other places it is from the south, as in the Alps of Europe, the Atlas ranges of Africa, and the mountains of northern Venezuela and the West Indies. Thousands of miles of the Tertiary ranges of North and South America are thrust toward the west, while important movements of the same age in the eastern Rocky Mountains were thrusts to the east. Taylor states that these are minor matters, and that the theory must be judged by the trend lines. Suess, however, recognizes these northward movements and concludes that they are derived from northward movements of one vortex in Africa and another in South America. It would seem that if a certain conclusion is drawn from certain facts in Asia, scientific principles demand a like conclusion from like facts in Europe and America.

As evidence of an actual separation of the northern continents from the north polar region, Taylor cites the outlines of the west coast of Greenland and adjacent portions of Labrador and the northern islands. According to Taylor, these coasts are linear and the lines of Greenland fit into those of Labrador, etcetera, to a marked degree, thus indicating, in his opinion, an actual partition of Labrador (and North America) from Greenland. Such a movement is, however, by no means the only conclusion to be drawn from such a parallelism, even though it be exact. If these straight coastlines are due to Tertiary breaks of one kind, they may be due to Tertiary breaks of another kind, and may be ordinary normal faults of Tertiary age. They may not be related to the Tertiary at all but may be Triassic faults. If man had been present during the closing stages of the glacial epoch he would have seen in the Connecticut Valley of New England a complete, though small, analogue of Baffin Bay, which now separates Greenland from Labrador. He might have concluded, therefore, that the crust of western New England had parted from that of eastern New England. Now that the glacial waters have receded from the Connecticut Valley, we can see, not that the crystalline rocks east and west of it have been dragged apart, but that a block of them capped by the Triassic has been faulted down between them. A similar explanation is perfectly reasonable and perfectly satisfies the known facts of Baffin Bay.

Furthermore, assuming that Labrador did recede from Greenland, what is the significance of the hole 200 or more miles wide which was

left between them? The depth of this hole is now 13,000 feet at the most, which is less than the depth of the Triassic floor in the Connecticut Valley. According to this theory, the present floor of Baffin Bay must be assumed to be somewhat nearly the floor on which Labrador receded from Greenland. This leaves for the thickness of the moving crust something between two and three miles. In order that this mass should slide southward in response to gravity, either the sliding plane must have an angle so high as to be inhibited by other facts, or the rocks of Labrador must have been drawn along from regions where the plane was at a high angle and must have been possessed of a tensile strength such as no rocks are known to possess. In short, the value to the theory of this assumed motion of Labrador is only that of a parallelism in outlines, a relation which may equally well have been produced by other means. Therefore, the relations of Labrador and Greenland, being susceptible of other interpretations, do not furnish positive proof.

No other evidence is given by Taylor in support of this theory, and, in fact, some of the evidences of direction of motion are set aside by him as immaterial. His case confessedly rests solely on the great trend lines of the Tertiary system, which phenomena can be explained in other ways and are so explained by geologists. A complete acceptance of Taylor's theory involves the acceptance of such extreme conclusions regarding amount of crustal transfer and of areas from which the transfer took place that the theory as it stands can not be accepted. It further involves a retardation of the earth's speed of revolution between the Carboniferous and Tertiary, of which there is no known evidence and for which there is no adequate cause. Retardation and slowing down caused by tidal friction have been appealed to by numerous investigators to change the speed of revolution, but critical examination of tidal effects by competent physicists and mathematicians has led to the conclusion that its probable effect is either nil or exceedingly slight. Therefore, to sum up, it seems that Taylor's theory of sliding of the continents from the North Pole down the hill caused by changing revolution of the earth rests on trend lines, which may be explained in other ways: it requires extravagant motions of enormous masses, it does not provide an adequate place from which they may have moved, and it assigns a cause of which there is no evidence and which probably did not accumulate and exert itself during Mesozoic time. Finally, the mechanism which he suggests to convert the radial pull of gravity into horizontal motion of the crust for hundreds of thousands of square miles meets in friction an obstacle to its acceptance which appears insurmountable.

The latest form in which the hypothesis of continental creep has ap-

peared is that of Wegener. In this hypothesis the crust of the earth is viewed in much the same way as in the Taylor hypothesis and is concluded to have moved freely for enormous distances. The direction of movement, according to Wegener, was from east to west instead of Taylor's north to south movement. While Taylor appealed to the outlines of Greenland to show separation of the mobile from the stationary crust, Wegener cites the shape of the western coastline of the Atlantic as compared with its eastern coast as an indication that the western hemisphere parted company from Europe and Africa and slid westward some 2,000 or 3,000 miles. The resemblance of outline on opposite shores of the Atlantic has been noted for centuries, but it is very crude and general and its discrepancies in detail are so huge—700 miles in the North Atlantic, for instance—that its value as evidence must be very slight. Before it can be accepted as any kind of proof it must be shown that there is no other explanation of the similarity.

Wegener's conception of the relations of land and sea is as follows: The continents consist mainly of masses of light rocks, sial, resting on a lower mass of heavy rocks, sima, which form a sort of shell beneath the seas and the continents. The rigid sial is supposed to be pulled over the yielding sima toward the equator by gravity acting on sial. In moving equatorward the continents acquire a westward lag or drift as they pass into belts of higher speed of revolution.

The reader may well wonder why the continents are not all near the equator, after some hundreds of millions of years of this process, instead of occupying their actual positions away from the equator. Yet the continents could not escape the equator in the end, because there would be no westward lag at all unless there were first some actual motion toward the equator. The combined movement must, therefore, have some southerly component which could end only at the equator. It is also questionable whether there would be any westward lag. If the southerly movement were rapid there would, of course, be a lag, but the motion must have been very slow, as the forces were very slight, and the entry of inertia and friction into the equation might well overcome all the tendency to lag.

The force called on to produce the southward motion is the slight pull of gravity on the protuberance of the continental sial over the sima. This has recently been calculated by Lambert from the respective densities and found to cause a horizontal pull of one millionth of an atmosphere. In his opinion, this amount should be between one million and one hundred million atmospheres in order to be effective.

The existence of any pull whatever on account of a protuberance depends on Wegener's assumption that the *sima* underlies the *sial* beneath the continents. This is not supported by evidence, but rather is the contrary probable, for the deepest parts of the crust which are exposed by erosion are characteristically granite—that is, *sial*. Furthermore, the great batholiths which have come up from still greater depths are in most cases granitic, or *sial*. Even granting that the *sima* does underlie the *sial*, there is no ground in the facts of geology for Wegener's further assumption that the *sima* would be readily pushed aside by the *sial* or would furnish easy sliding for it.

It must be recognized, furthermore, that any cause assigned for this huge translation must have come into being since Tertiary time, because the Tertiary ranges of Europe and of northern Africa are cut off at the eastern Atlantic coast where North America is supposed to have parted from Europe. If Spain and adjoining Africa could be forced into contact with North America, it would be found that the Tertiary ranges of Spain and Africa trend about east and west and are strongly folded, while in America there is only slight tilting along lines trending northeast and southwest. The same relation would obtain if the Appalachians in Newfoundland were forced into contact with the same system in Great Britain. The American structures trend nearly north and south, while those of Great Britain trend about east and west. These complete discordances of structure on opposite sides of the Atlantic are supported by others to such an extent that it is clear that visible structures are in direct contradiction to the theory.

The relation of the Tertiary ranges above described reduces the possibilities in the way of cause to such as may have grown during the Quaternary. An examination of the Quaternary beds of eastern North America, however, which must under the theory have moved more than 2,000 miles, shows that they are almost undisturbed. It is inconceivable that such a tremendous transformation could have taken place without enormous dislocations and upheavals of the Quaternary and Tertiary beds. From the observed Pleistocene structural geology this theory receives only a flat contradiction.

Wegener cites in support of his theory certain resemblances of faunas in regions that are widely separated, the argument being that because they are very similar they must have been deposited close together. The fallacy of this argument is readily shown by the facts. Suppose that the Cretaceous beds had overlapped the Appalachian system a little farther and had covered the central part of it. Wegener would then have been justified in assuming, for instance, that the range had been pulled apart

for 1,000 or more miles, because the faunas are the same on both sides of the gap. Appalachian faunas, however (and others as well), extend for two or three times that distance with little change, so that mere amount of separation affords not the slightest ground for Wegener's argument.

The hypothesis apparently must, therefore, fall back on a cause which is of the order of the special convulsion of nature appealed to in the early stages of geologic work. Such a convulsion, which affected a whole hemisphere, could have no probable cause except one of an astronomic nature. A cause of similar nature is mentioned by him in the form of a shifting of the poles. Such a change has long been considered by astronomers and physicists, with the conclusion that it can not be conceded to have taken place, in view of astronomical data, at a date recent enough even to approach the period required by this hypothesis.

SUMMARY OF THEORIES

In summing up the main points of the various theories of mountain-building, it appears that all of them are opposed by one or more of the great geologic facts, while most of them receive support in some direction. All of the theories so far proposed depend mainly on some cosmic factor. The principal factor of this kind is gravitation; others of importance are the secular loss of heat, a change in the rate of revolution of the earth, and a shifting of the axes of revolution. Some theories combine several of these factors, and they do so with the more or less plain desire of making up for shortcomings in the quantitative results of any one of these causes acting alone. The principal deficiency is in connection with the horizontal motion so plainly evident in the folded ranges. Another great discrepancy lies between the continuity of the forces and of the results, while a third obstacle is in the friction involved.

The deficiency of horizontal motion which would follow from the old hypothesis that folding was due to condensation of the earth and radial contraction has long been understood. Numerous calculations have been made as to the amount which would follow from condensation due to loss of heat. These calculations are based on the observed increase of heat downward in the earth and the known conductivities of the substances of the crust and of the atmosphere. There is general agreement that the amount of lateral shortening obtainable in this way was seriously short of the requirements. The earth is no doubt shrinking, and this in time causes lateral compression. The time allowable in the case of the Appalachians is only that of the Paleozoic, for the Precambrian deformation must be considered to have absorbed earlier shrinkage. It has been

found, however, in calculating the shrinkage necessary to account for the folded mountains, that Paleozoic time supplies only a small fraction of what is necessary. The time required is so great that other major differences are entailed, such as speed of revolution and its results. Furthermore, the great relations of ocean and continent were so substantially the same during the Paleozoic that geologists can not admit major changes of the earth's plan during that era. If new calculations are made, based on the true amount of Appalachian shortening, the discrepancy will be thrice as great. The same quantitative difficulty is met by the advocates of lateral thrust from the sea-floors. This also is understood to go back to contraction of the earth for its cause. This theory is, therefore, subject to the same limitations of quantity as are the older theories depending on contraction. It must be conceded, however, that there is some lateral thrust from the sea-floors, unless all contraction of the earth is denied and unless the greater density of the crust beneath the seas is disputed.

No such troubles disturb the advocates of continental creep. Taylor's theory calls for a southward movement of 2,500 miles in the Malay lobe, while Wegener bespeaks 3,000 miles of westward travel for South America. Wegener thinks that North America has crowded over against Asia, but the connection of Asia with America through the Aleutian Islands is one of the most beautiful structural units of the globe and clearly permits of no accidental piling up of America on eastern Asia. The buoyancy of America on the sea of sima was not shared by Asia, for some unexplained reason, so that Asia was left in the lurch. "Westward ho!" for America is thus of venerable antiquity. The quiescence of Asia, however, does not appeal to Suess, who assigns to Asia the active and oft-repeated rôle of a vortex of diastrophism.

It should be borne in mind that the theory of lateral movement of great masses is not new; it is the necessary consequence of the shortening observed in mountain ranges. The present theories of continental creep merely extend the movement over vastly greater areas than older theories. All of the theories, however, unite in one thing: they regard Africa and India as negative elements; even the Wegener theory, which pushes the continents around so freely, has left Africa unmoved. During the troublous times of the Quaternary, according to the Wegener theory, Africa may thus have afforded a safe refuge for the preservation of man, and the theory should have pointed out the desirability of search there for Tertiary man. The present backward condition of the African races might thus be traceable to their freedom from diastrophism and its

injurious results. It further indicates the wisdom of the selection of central Africa as the site of the Garden of Eden.

The hypothesis of a change in rate of revolution must account for a probable lateral shortening of the crust of about 10 per cent, according to W. B. Taylor. This would necessitate an enormously higher initial speed, such that the day would have been only four hours long. If, for the sake of argument, this were granted in the case of the Tertiary folding, what would be left of the day, for a similar change would be required for the Carboniferous, and still other changes for the Precambrian? The hypothesis advocated by W. B. Taylor in 1885 (slower revolution and raising of the poles) depends on this very factor. Postulating an increased revolution, F. B. Taylor, in 1909, attributed to it an east-west belt of folding around the world with the motion southward from the north pole. W. B. Taylor, however, attributes a set of north-south folds greatest near the equator. Chamberlin sees, as a consequence of such a factor, north and south folds near the equator and also tension cracks near the pole, and concludes from the absence of such phenomena that the slowing down has not affected mountain-building. Willis figures an outward thrust from the oceans in all directions against the continents.

Hobbs views the same outlines of the Tertiary ranges as Taylor, and concludes that the motion was northward, directly the opposite of Taylor's conclusion. Taylor supports his conclusion by the pattern of the Greenland and near-by coastlines; these, he thinks, show a separation of 500 to 1,000 miles, the movement being southward from the polar area.

Wegener, reasoning from similar features—that is, coastlines which have a rough similarity of outline—postulates that what is now the Western Hemisphere moved westward from 2,000 to 3,000 miles. This motion, according to him, was progressive from the Paleozoic to the present time. Geologists can not believe, however, that the continents should have slid for thousands of miles during the Quaternary and have left no record in the attitude and character of the sediments. Even if the minute forces appealed to by Wegener did become operative, their pull would have been southward toward the equator and not westward along it. Thus Wegener sees certain outlines resulting from westward continental movements, while Taylor sees them resulting from southward movements. In both cases the facts can be explained as well or better in other ways. No attempt is made to explain why the sial of Africa did not feel the pull of gravity.

Another great obstacle which must be overcome by all of these theories, and particularly by those of continental creep, is that of friction due to

the moving of the crust on the interior of the earth. This is, of course, proportional to the weight and thus to the thickness of the crust involved. Neither Taylor nor Wegener gives any idea of the thickness which he regards as likely, but appears to regard it as a superficial matter. It is, nevertheless, a matter of prime, and even of destructive, importance, in view of the minute force relied on to cause the creep. Thus, the moving crust required by Taylor, thickening to the south from a minimum of three miles in Greenland, would acquire a prohibitive thickness long before it reached southern Asia. Wegener makes no statements as to the thickness of the crust, but his diagrams convey the idea of a crust of light rocks floating with comparative freedom in a sea of heavy rocks. This arrangement, to his mind, appears to require no particular friction, but such a conception will hardly be accepted by scientists in general. Lambert states, moreover, that the horizontal pull available from density differences is only one-millionth of an atmosphere—a strikingly small force. In fact, Daly, in an attempt to render this hypothesis workable by getting rid of this enormous friction, has postulated a layer of glass between the crust and the deeper earth which would afford a minimum of friction. This is, however, only a postulate and can hardly be supported by evidence. Thus, the ease of motion which a lateral creep of the continents would require is an obstacle which is likely to remain a permanent one. It is also a real difficulty for all theories.

It will be evident from the foregoing summary that no theory of mountain-building is free from serious objections. In some cases the objections are far more weighty than the arguments in favor, while in others there is a body of probability. Such a situation is only to be expected from the nature of the process, which took place in the depths of the earth and whose results have in large measure remained there. However well supported a theory may be by mathematics, it can not prevail unless it satisfies the conditions laid down by the visible rocks, and it is for that reason that the tests by geologic facts which are known and can be reaffirmed have been made the prime consideration in this discussion. The theory which is to last must explain all the facts, but first those of geology, for the problem of mountain-building would have been unknown except through the rocks. We may well wish for more facts, and we are gradually getting them. Accordingly, the theory proposed in the next section has been derived directly from the geologic facts. It appears to satisfy the phenomena of the Appalachians, not only the usual but the exceptional ones, and it may solve the difficulties in other mountain ranges.

BATHOLITH INTRUSION AS CAUSE OF FOLDING

GENERAL STATEMENT

The analysis of the theories of mountain-building has shown that each theory has serious drawbacks. The principal of these drawbacks are (1) that the continuity in effects required by the theories is in contrast with the irregular intervals shown by the facts, both in time and in space; (2) the difficulty of securing the amount of horizontal motion which is evident in the folded mountain ranges; (3) the slightness of the initial force appealed to in contrast with the enormous obstacles of friction and cohesion presented by the rocks; (4) the extensive revolving of the crust between the sea and the land required by some theories—a situation which has not taken place since the Paleozoic began. The author's analysis of the theories has led him to the conclusion that another force has operated which is not continuous in time or space and which was not deficient either in initial amount or in horizontal motion. In the search for such a force, which must be a great one, he has been led to consider other phenomena attendant on mountain-building. These are (1) heat, which is evidenced by metamorphism and the growth of new minerals in the deformed rocks; and (2) the force exerted by igneous intrusions.

The association of igneous intrusions and extrusions with periods of mountain-building has been observed and commented on by many writers, but in all cases known to the author the intrusions have been regarded as results of the mountain-building forces and not as their cause. It seems to the writer, after much consideration, that the case is reversed and that igneous intrusions, which are the greatest examples of heat and force known to us, and which are definitely associated with mountain-building, should be rated as the cause of the building of mountains, which show to us the greatest known results of heat and pressure. In the demonstration of such a relation the same difficulty is encountered by this theory as by others—that is, that the forces and the moving masses acted deep within the crust and must in the main be beyond observation. In most mountain ranges only a few thousand feet of the crust are observable; in the Appalachians, however, parts of the crust have been uplifted so high and worn so deeply by erosion that the observer can examine rock masses which originally lay many miles beneath the surface. The conclusions drawn from direct observation in the Appalachians should have special force, therefore, and should be regarded as the best test which we now have of the theories of mountain-building.

PROBABILITIES

The probabilities in regard to the hypothesis of batholith intrusions are as follows: An association of igneous intrusion with mountain-building is well known, and in the Appalachians enormous batholiths were intruded at the time of Appalachian deformation. Unless these batholiths were under a pressure of their own, equal to or greater than the pressure of the hard parts of the crust, they could not have entered the hard crust; or if, perchance, they had entered before the pressure on the crust began, they would have been promptly squeezed out by the harder crust, like water from a sponge. The igneous rocks must, therefore, have entered the crust after the deforming pressures began and thus must have been under a pressure greater than that of the crust itself. It is rational to conclude, therefore, not that there were two independent pressures, one for the crust and one for the intrusives, of similar amount and different origin, but rather that there was one force and the same for both crust and intrusive. Force, therefore, lay in and began with the intrusives; otherwise they could not have entered the crust. There is no probability that igneous intrusions would be rhythmic, for it is not known that they depend on long-continuing causes like contraction through loss of heat, or on any cosmic phenomena, such as change in rate of revolution of the earth. In this respect the theory accords with the lack of continuity or rhythm displayed in mountain-building.

Most igneous intrusions show great force. This is particularly true of batholiths, laccoliths, and sills, which plainly have forced apart enormous rock masses or have lifted huge piles of overlying strata. The force exerted is shown in detail in the shattering and rending of the rocks. While many flows and dikes do not appear to have been under pressure, yet the fact that they reached the surface at all and kept their channels opened is evidence of considerable pressure in their depths. What we now see of them are chiefly the portions which were released from pressure. If it is true, as it seems to be, that open spaces can not exist a few miles deep within the crust, it is clear that any igneous rocks which were deep-seated enough to be molten must have been under heavy pressure or their channels would have remained closed. That this force is quantitatively sufficient for mountain-building seems clear from the fact that it is greater than the strength of the crust, for it has repeatedly shattered the crust and moved the parts around. The argument from probability is, therefore, distinctly in favor of this hypothesis, inasmuch as the great intrusive masses have had the requisite heat and pressure to deform the crust greatly and have been associated with mountain-building.

ANALOGIES

The argument from analogy is similar in its import. It is clear from the phenomena of sills and laccoliths that enormous masses of the crust have been moved by intrusions. Laccoliths a mile or two in diameter are common, and their formation required force enough not only to lift the overlying beds but to bend them at considerable angles. Sills are of much greater extent and are measured in tens of miles, and they performed a correspondingly greater amount of work. It may be objected that these are local and not of the same order as the folded mountain ranges. No such objection can be raised, however, to the batholithic intrusions in the southern Appalachians. The longest batholith now known in the Appalachians is 350 miles long, with a width of 30 or 40, which clearly puts the batholiths in the same order of magnitude as the folding which runs parallel with them. These batholiths are composed in the main of biotite granite and have a strong likeness from one end of the Appalachians to the other. The probability is strong, therefore, that some sort of connection existed between the various masses and that the parts now visible are only the tops of far greater masses. Many of them have dome-shaped tops and have pushed up the inclosing gneisses from below.

Evidence of a similar nature in regard to magnitude is furnished by the enormous outpourings of lava on the surface. Those of India are considered to show a mass of lava of 200,000 cubic miles. A similar order of volume is shown in the Columbia River lava flows with its 50,000 cubic miles. Local evidence on this point is furnished by the great system of Triassic dikes and flows of the Atlantic seaboard. These extend in a zone from Georgia to New Brunswick, some 1,200 miles in length, and the width of the belt is from 20 to 100 miles. This implies a large body or connected series of bodies of magma and a force which actuated them through an area nearly as extensive as the Appalachians. Single dikes of this system with a length of 10 miles are numerous, and they have a maximum of 20 miles.

The phenomena of intrusion shown along the Atlantic coast in New England and Canada are very instructive in regard to the quantitative element in batholithic intrusion. In that region the rocks were scraped clean by continental glaciers and are now kept bare by the waves of the sea, so that they furnish a remarkable series of exposures. The amount of intrusive matter there exhibited is enormous and locally far exceeds in volume the rocks which suffered the intrusion. An estimate of 50 per cent of bulk of intrusive matter is reasonable for large areas.

By analogy of similar cases, therefore, this theory of batholithic intrusion is supported in regard to the quantity of matter intruded, to the geographic spaces involved, and to the pressure necessary to accomplish the visible results.

EXAMPLES

The argument from example is necessarily more restricted than the arguments from probability and analogy, but its tenor is the same. It has been a matter of repeated comment that igneous activity and mountain-building were substantially coincident in many regions and times. Both in the northern and southern portions of the Appalachian system enormous masses of granite were intruded in great batholiths at substantially the time of the folding. In the central part of the Appalachians (Pennsylvania and Maryland) the facts are largely concealed by the Cretaceous deposits, but enough area remains to exhibit a few of the batholiths of the same age as the others. That more are concealed beneath the Cretaceous is probable from their eastward increase where the system is more widely visible. They were intruded under great pressure, as is shown in thousands of places by the shattering and rending of the country rock. Thousands of dikes lead off from the batholiths and hundreds of sills are associated with them. The width of the now visible portion of individual batholiths (as great as 30 miles) is proof of an enormous amount of separation of the country rocks—an amount which is enormously increased by the distention due to sills and dikes. It may be objected that a large part of this apparent distention is merely substitution of the batholith for the country rock with removal of the latter, or perhaps digestion of it. In answer to this, it may be said that while there is evidence of digestion it is limited to the margins of the batholiths, whose general composition remains unaffected over enormous areas. In detail the contacts of the intrusive bodies are sharp, they cut across layers of the country rock cleanly, and there is no evidence of anything in the form of general substitution. On the contrary, where detailed mapping has been done, in North Carolina, for instance, the thrusting and wedging action of the scores of sills and tongues is particularly clear. A lifting and doming action is well shown in the Pisgah region of North Carolina (Pisgah folio, United States Geological Survey).

The ground plan of the batholiths in relation to that of the folding is highly instructive. The two main foci of intrusion are at the north and south ends of the Appalachians. Parallel to these intruded areas, and just northwest of them, is seen the greatest development of thrust faults,

the greatest northwestward advance of the great salients of North Carolina, Pennsylvania, and Vermont, and the greatest development of metamorphism. The chief exceptions in Appalachian structures, the fan structures, are in complete accord with the theory, but are not otherwise explainable. If the theory is true, then the area between two groups of batholiths should be compressed from both sides and should be raised less than the masses over the batholiths. This is the relation observed in all determinable cases known to the author.

In the eastward representative of the system in Great Britain the post-Carboniferous granites and the disturbances caused by them have long been known.

It seems impossible that such agreement in relations should be mere coincidence. No other theory of mountain pressure even begins to account for the systematic grouping of the Appalachian structures, and many of the discrepancies of other theories are plain, in view of what has already been stated. That batholiths are an adequate cause, however, is indicated as probable by the heat and pressure which they possess. Other intrusive masses have deformed large sections of the earth's crust; great batholiths were intruded at the time of the Appalachian folding and did distend the crust; and the areas of their principal intrusion accord with the areas of maximum thrust, metamorphism, and general advance of the crust in the salients. Since, therefore, this theory is in general possible and involves only known principles; since it satisfies the probabilities as to amount and character of force; since similar activities have produced analogous results; and since the visible intrusions are in perfect accord with the very diverse requirements of Appalachian structures, it seems a well founded conclusion that the theory is in the main sound. There is no call on unknown forces or unknown conditions in the earth's crust—only those which are known and can be verified.

METHOD OF ATTAINING HORIZONTAL MOTION

FLUID CONDITION

The chief difficulty to be solved by this theory of mountain-building is, as in the case of other theories, that of producing horizontal motion. This theory has a decided advantage, however, in that the hydrostatic element is involved in its action. Theoretically magmas are fluid or substantially so, and the local evidence of their condition which we can now see in the rocks indicates fluidity. It scarcely needs mentioning that the intrusive material of dikes, sills, etcetera, was fluid. The evidence is equally clear for the batholiths, though hardly as striking. The mar-

gins of most, if not all, batholiths show vast numbers of intruding dikes and sheets which extend for long distances from the main body and are of all dimensions, even down to inches. The actual flow of the material is shown by the wavy banding near the contact (flow banding), by the strings of inclusions along the contacts, and by the finer grain of the intrusive where it was chilled near the contacts. Therefore, since the intrusive material was sufficiently fluid to move freely under the pressures which affected it, it is clear that a hydrostatic condition prevailed in the magma as a whole. That being the case, any pressure applied to any considerable part of the magma was transmitted throughout its mass. If the fluidity were perfect, as in water, the pressure would be equal throughout the mass, but in proportion as the viscosity increased so the pressure transmitted would diminish. Furthermore, whatever was the direction of the initial pressure, the pressure transmitted would be at right angles to all confining surfaces, if the fluidity were perfect. In proportion as the fluidity was less, the direction of the transmitted pressure would approach more nearly that of the initial pressure. In the batholiths which have been observed a fluid condition is apparent, so that there can be no serious doubt that the hydrostatic condition prevailed, and that any pressure applied to any part of the batholith was transmitted in large measure to all of its mass and further transmitted at right angles to the confining walls.

ATTITUDE OF ROCK PARTINGS

In applying this conclusion to the problem in hand it is necessary to consider what were the most likely attitudes of the confining surfaces of the batholiths; in other words, in what shape would the country rock break when the batholith was intruded. It is easy to see that the sedimentary rocks would part freely along their layers and that schists and gneisses derived from them would do the same. The same is true to a less extent for the banded gneisses which have a layered condition, but in which the layers are more or less interlocked by mineral crystals. The massive rocks, like granite and diorite, would be entered with the greatest difficulty. In the granites of the Precambrian, however, which would necessarily be traversed by the Devonian and Carboniferous granites, there has been a large amount of shearing. This has caused many zones of sheeting, and even of thin schists along which partings would easily be made. Opportunity for intrusion of igneous material would thus be far greater in layered or sheeted rocks than in others, so that they practically control the separation of the country rock in order that intrusion may have taken place.

The attitude of the planes of layering and sheeting is of first importance in determining the direction of pressure put on the country rock by the batholiths. The planes of parting as we see them exposed at the surface have high dips—from 45 degrees to vertical. Over enormous areas vertical dips are more common than any other. It is, therefore, clear that, when these highly inclined schists part, the openings also will have high inclinations to the surface of the earth and that the intruding masses will have similar attitudes. That such was actually the case can be seen at countless localities in the southern Piedmont of the Appalachians. The separation of these highly inclined layers is therefore largely in the horizontal direction; in other words, in the direction needed to accomplish the observed lateral thrust.

It may be argued that part of this steep dip in the Precambrian is due to folding during the Appalachian revolution, and such may be the case in part. There were, however, strongly inclined Precambrian rocks before the Appalachian revolution, and the structures due to that revolution are imposed on those of earlier date. Furthermore, high dips of the foliation and schistosity are characteristic of the Precambrian throughout America, and in many areas where Paleozoic or later folding is gentle, such as the domes of the Adirondacks, of Wisconsin, and of the Black Hills, there is much high tilting of the Precambrian layers. It is clear, therefore, that there were steeply inclined partings in the Precambrian rocks developed before even the deposition of the Paleozoic rocks, so that the structural conditions of steep parting planes were present, regardless of what happened later in the Appalachian folding.

We can not be sure, however, that this general high inclination of the rock partings goes down indefinitely into the crust. Indeed, it is probable that such is not the case. With increasing depth below the surface the rock pressures are greater in the vertical direction, which would naturally result in the production of partings more and more nearly normal to that pressure; in other words, approaching the horizontal. This condition must yield to another still farther downward in which the strength of the rocks is wholly overcome by the vertical pressure, perhaps to such an extent that they have a potential freedom to move in any direction. This might produce a condition resembling fluidity, but one which would require the application of enormous force to cause any change in the position of a particular mass.

There is some evidence that this condition of horizontal partings does exist in the deeper masses. Of course, approximately horizontal partings are by no means unknown in the Precambrian rocks, but the difficulty lies in ascertaining how deeply they were buried. The determination of

this can only be made in the proximity of sediments which fix the relative position of the surface of the earth. Much detailed work is also required, and a considerable separation of the Precambrian into different formations must be possible. These three factors are best combined, so far as now known, in western North Carolina. In that region the great border thrust faults have brought up the most deeply buried masses in the Appalachians. These have been stretched and sheared along countless planes which approximate the horizontal over large areas. The amount of actual horizontal motion as determined by the elongation of crystals is as great as 10 to 1. In this single instance, therefore, the deeply buried rocks do have low angle partings. It is, of course, not safe to generalize from this instance, but it is clear that such a condition exists in places, and it may be general.

If horizontal partings in the lower portion of the crust are general, the effect of this on the transfer of magmas is obvious. The easiest path for the magmas would there be in a horizontal direction, without much lifting of the entire crust. In that way might be explained the similarity of batholiths over enormous areas—a fact which is apparent in the Appalachians, and which has been noted in many parts of the earth. Such horizontal planes would lead naturally in the upper layers of the crust to the more highly inclined planes which we now observe. No break would be expected between the horizontal and the inclined planes, and therefore none between major batholiths extending horizontally at depths and those which extend upward at high angles toward the surface. Such a general arrangement, while of course highly speculative, meets the general requirement of the observed facts and is easily within the general possibilities.

INCLUDED GASES

There are two additional phenomena in connection with the intrusion of batholiths which doubtless lend their assistance in causing some of the phenomena of mountain-building. These are the explosive power of gases and the pressure of growing crystals, both being directly connected with the gain or loss of heat. The presence of gases in igneous rock has long been known, and sufficient evidence of their existence and tremendous force is seen in the explosion of volcanoes. In recent years it has been determined that the explosions are due to steam and that the lavas have a considerable content of water. It has also been known that granites, the principal rock of batholiths, contain an appreciable amount of included water. This is shown not only by direct inclusions of water in crystals, but on a large scale by the solutions which pass from granites

into the country rock. While these granites were in the fluid stage the expansive power of this included water and other vapors which are known to be associated with batholiths must have been enormous. A definite vapor pressure of atmospheres becomes, when applied to the walls of batholiths hundreds of miles long, a truly enormous force, fully capable of rending the rocks of the crust, just as it visibly rends those rocks where volcanoes exist.

GROWING CRYSTALS

It has been long known that growing crystals exert a tremendous force; the most familiar case is that of ice, but other instances are matters of common knowledge. Mineral crystals which grew later than the body of a rock can be seen to have distorted the rock and pushed it aside as if it had no strength. Many attempts at measurement of this force have been made, but only recently has the equipment and the effort been sufficient. It has lately been determined that growing crystals exert a pressure of 1,000 to 2,000 atmospheres on their confining walls. If this pressure is applied to the wall of the batholith during the cooling of the magma it becomes a force of the same order as that of the vapor pressure in the magmas. It follows the vapor pressure after the magma has cooled so far that the vapors are condensed and crystallization is well under way. The pressure of growing crystals, while very intense, causes a very limited motion. In this respect it is quite unlike the vapor pressure, which is capable of enormous motion. The pressure of such crystals may, however, have applied the pressure to the crust which has obviously been at work in the metamorphism of the rocks where mountain-building was strongest. This combination of the pressure of crystals, together with the pressure and heat of the batholiths, seems to explain the association of metamorphism with mountain-building and batholithic intrusion.

BEARING ON OTHER THEORIES

The distribution of batholiths suggested above affords an explanation of many relations which are of fundamental importance but are extremely puzzling. Such are the epeirogenic uplifts of large regions, the uplifts of large and small domes, and the reversal of such movements. These have been mentioned already as grave objections to accepting isostasy as a prime and sufficient cause of mountain-building. If, however, there may be general movements of magma at depths (and it is clear that they do take place locally), the situation is quite different. Magmas would find the weak parts of the crust and push them up into domes, probably doing so again and again in response to successive im-

pulses. When magma was expelled from one region it could move laterally and raise another region. In this manner we may reasonably explain the persistence of certain areas (probably those of weakness) as domes or ridges and the repetition of movements on them so often shown in the Paleozoic. It should be clearly noted that this process is reasonable, since it depends on only two factors, fluidity of magmas and horizontal partings at depths in the crust, both of which are known to have existed.

Magmatic movements also have an immense advantage over isostatic underflow in that the moving masses are fluid, and not solid rock with friction and rigidity to be overcome. Independent evidence that magmas moved at depths is seen in the fact that batholiths are deep-seated, for they are only exposed by removal of a thick cover of sediment. In fact, if they had been formed near the surface, they would have found that resistance was least to an upward movement and they would have exerted little lateral pressure, which is not found to be the case. The corollary to this is the conclusion that they were deep-seated and that, since they did move horizontally for long distances, they found horizontal channels for easier lateral transfer. Under this conception the volcanic plugs which cut the Paleozoic rocks in a few places may rise from the tops of batholiths, boring and pushing their way upward and perhaps lifting the small domes which can not be explained by lateral compression.

The lateral movement of magmas has another close relation to isostasy. As has already been noted, isostasy is a leveling process and requires some starting cause—something to upset equilibrium. It seems that magma transfer on the scale visible in the Appalachians meets the varied requirements. It could start uplift and bring isostasy into play, and it could renew or reverse uplift, as has been repeatedly done. Furthermore, the existence of magma bodies with some ease of transfer might permit the relatively small factors of erosion and sedimentation to become operative and adjust the crust. Isostasy in the extreme form recently advocated demands a mobility of the crust that does not seem possible unless fluid masses are involved in some part of the column. If fluid masses are involved, and unquestionably they have been in the past, it is probable that isostatic compensation is accomplished in them. Its depth would therefore be controlled by the position of the batholiths and be a variable quantity.

It is further to be noted that the existence of granite batholiths at depths of 10 or 20 miles does not require an indefinite downward extension of them. Below the zone in which batholiths are known to have

existed there may be rocks with the rigidity which astronomers think is required for the earth as a whole.

The intrusion theory resembles the theory of suboceanic spread, for each takes account of the same condition of greater density beneath the oceans. Suboceanic spread, however, must overcome the strength of the solid crust before it can produce great results in lateral motion, and there is no assurance that the motion will be cumulative and confined to one belt. The intrusion theory also resembles that of isostasy in that both appeal to gravity as the moving cause. So, in fact, do all theories on this subject. Isostasy, however, starts with erosion of matter and its deposition elsewhere as a cause of differences in gravity. Intrusion, however, has been independent of these factors and has often overcome them. Finally, the mechanism suggested for the intrusion theory differs from that of isostasy as fluid rock differs from the solid; indeed, it offers a means of making isostasy more effective.

ULTIMATE FORCES

GENERAL STATEMENT

A conclusion that the intrusion of batholiths is the immediate cause of mountain-folding (or that any other cause is the immediate one) by no means solves the final problem. Whatever is the immediate cause, back of that is some initial force, and the question arises in this case, What force lay behind the batholiths that compelled them to break their way into the solid crust? Two initial forces and two only are available for this work, namely, gravity and heat.

HEAT

The heat may be that which remained from the initial heat of the earth after condensation from a nebula, or it may be that derived from the slow accession of meteorites or from the direct heat of the sun. Probably all of these sources of heat are at work, but it is difficult to see why an initial heat of the earth from condensation is not by far the greatest. The sun's heat no doubt retards greatly the escape of the internal initial heat, but no mechanism has yet been suggested for converting this heat into a cause of deformation. It has, however, been urged that newly deposited sediments cause a rise in the isogeotherms with attending expansion of the crust. Such a rise, however, is not due to the heat of the sediments derived from exposure to the sun, but to the fact that the sediments may act as a blanket to prevent the loss of the initial internal heat.

The heat derived from the fall and accumulation of meteorites is exceedingly small in comparison with the mass of the earth, and it is very difficult to show that a concentration of it is probable either in time or in space so as to answer the requirements of mountain-building. Any hypothesis of a special accumulation of meteorites to account for a period of diastrophism must necessarily be purely speculative. If there were such an accumulation, which could be caused only by passing through an unusual swarm of meteorites, such a passage would be rhythmic and repeated at similar intervals in the earth's history. There is no evidence of such rhythm, but rather the contrary. Still less is there evidence of special concentration of meteorites in certain parts of the earth, and it is difficult to see how such could be the case, on account of the rapid revolution of the earth and the exposure of all of its parts to the fall of meteorites. Finally, it is questionable if any meteorites are warmer than outer space until they reach the atmosphere. Therefore, it is not easy to understand how they could heat the earth's interior to temperatures higher than their own.

Owing to the existing difficulty of demonstrating the primal source of the internal heat of the earth, we can at present do hardly more than accept its presence and its great downward increase and adjust to that condition our theories of mountain-building.

GRAVITY

The other great fact of the world, gravity, must of course be the major part of the theory, just as it is the most compelling force in the universe. The gravity may be that inherent in the mass of the earth itself or between different parts of that mass, or it may be the gravitative influence exerted by the planets or other heavenly bodies. There is no motion of the crust in which gravity is not concerned in some way, even if not as the principal cause. All investigators agree that its power is great enough to cause any of the effects that we see in mountain-building, and both through theory and observation we know that the rocks and minerals of the earth's crust are unable to resist gravity indefinitely. Its power is tangibly shown in a multitude of phenomena: the falling bank of earth, the rocks breaking from the cliff, the landslide covering miles, the toppling of mountain peaks, and the sliding of thousands of cubic miles of glaciers. The greater the masses involved the greater are the forces exerted.

The chief difficulty in establishing the connection between gravity and mountain-building lies in the facts that the pull of gravity is chiefly downward toward the center of the earth and that the pull must be

diverted into the horizontal in order to explain the observed results. In the previous section a mechanism for attaining this diversion was outlined, the principal requirement of which was hydrostatic pressure. If that condition is granted, and it is difficult to deny that it exists, the means of diverting the downward pull of gravity seems ample. It will no doubt be conceded by advocates of isostasy at least that such fluidity is reasonable and proper at some depth, in view of the mobility which that theory requires even from solid rocks near the surface, not to mention the return flow of deep-seated matter from beneath the sea to the land.

For final analysis of the problem, let it be granted that an excess pressure of gravity was transformed into lateral pressure through batholiths whose magmas were practically in a hydrostatic condition and that this pressure built the mountains. The questions next to be answered are these, On what part of the crust was this excess pressure exerted and why was it exerted?

The direction in which lay the unduly pressed crust can be readily inferred from the direction in which the crust moved when yielding. That motion was from the southeast to the northwest, in the case of the Appalachians, and it is on the southeast, therefore, that the heavy part of the crust was situated. Since the effects extend from the Gulf of Mexico to Newfoundland and probably across the North Atlantic into Europe, the locus of greatest pressure was probably under the Atlantic, where the normals to the trends of the system intersect.

What, then, are the features of the Atlantic that bear on the second question? Two major points are crucial: First, it has been fairly well determined by the observations of years that the rocks visible on the shores and islands of the oceans are denser as a whole than those of the continents. Second, gravity observations made instrumentally in recent years seem to show that the force of gravity, and therefore the densities, is greater in and around the oceans than on the continents. Mathematical analyses of gravity differences are made which indicate that they are compensated within and do not extend below a depth of 60 miles.

If, then, we accept as a fact the greater density of the crust under the oceans, there is provided a downward pull of gravity in one region greater than in adjoining regions. This would tend to depress the ocean bottom. A depression could be actually accomplished by further condensing the underlying rocks or by lateral movements of the crust. It is reasonably sure that all condensation compatible with other conditions took place at an early stage, so that depressions to satisfy existing densities would be attained by lateral movements. If by any means any down-

ward movements were started, the domed shape of the sea-floor would become a factor and would transmit lateral thrust in all directions from the center of depression. The distance to which this thrust would be transmitted would be in proportion to the thickness and strength of the crust which was depressed. If the depressed portion were 40 or 50 miles thick, a horizontal transmission of even a thousand miles would be reasonable. A phenomenon of this order is comparable with those of the Appalachians, and a depression near the middle of the North Atlantic would affect regions at the distance of the Appalachian Mountains. It is from possibilities of this sort that the hypothesis of suboceanic thrust finds its support, as well as in the general arrangement of mountain chains near the ocean margins.

To carry the analysis still farther, let it be assumed that the ocean-floor settled and thrust against the margins of the continents. This thrust would not be transmitted indefinitely, but would somewhere reach a weak belt. Yielding to the strain would ensue, and either folds or faults would be caused.

Let it be further borne in mind that there are reservoirs of molten matter at some depth in the crust. The positions of these were doubtless adjusted to the general set of pressures prevailing before the first subsidence began. New and greater pressure on them would certainly cause changes of position, fresh channels would be forced open by molten material, and these must needs tend to spread toward the regions where pressure had been released around the faulted sea margins. Once the system of adjusted pressures was upset, the mechanism of batholithic intrusion was put into action, with the probable result of deformation.

A general subsidence of the western Atlantic floor by one mile would expel 4,000,000 cubic miles of material. This amount, translated into batholiths and folding, is enough to account for the lateral shortening of a mass 2,000 miles long, 10 miles deep, and 400 miles wide into half its width. In short, so far as quantity is concerned, a subsidence of the Atlantic floor by one mile could produce the Appalachian system. Such a subsidence is a moderate one, and movements of such magnitude have not been rare in the geologic past. On the contrary, oscillations of the sea-floor have been so numerous that they may be regarded as a normal characteristic, from the beginning of the Paleozoic to the present.

The force available to propel the intrusive masses and effect the folding was that of gravity, and its measure was the difference in density between the oceanic and continental parts of the earth's crust, perhaps as much as 5 per cent. When this is translated into terms of weight for columns of ten or more miles in depth, it is truly a formidable force.

The wonder is, not that it was able to lift mountains, but that it has not long ago crushed out all differences of density. The application of this force to any part of a reservoir of magma would endue the latter with power to rend anything else. The only thing capable of preventing it would be the same pressure on the rocks restraining the reservoir and in a state of equilibrium. When once this adjustment was disturbed, however, the consequences in intrusion and folding were almost inevitable. An important factor should be pointed out—that is, that the force of gravity was not exhausted by any one sinking of the ocean-floor. It remained just the same, ready for action again if there was release around the margin of the sea.

A review of Appalachian structure brings out some highly interesting coincidences. The gradual increase of oscillations through the Paleozoic, and the establishment of scanty areas of folding in the Ordovician and of greater ones in the Devonian, point to the gradual upsetting of crustal balance. This was consummated at some time in the Pennsylvanian by formation of the great overthrusts of the mountain border zone, which may well represent the outthrust of the domed sea-floor. Its collapse followed in the Permian, with intrusions and folding. The great shear planes of the first overthrusts were themselves folded and faulted, in many places to as great a degree as the strata themselves. In the later stages the pressure of the folding and the heat and pressure of the batholiths metamorphosed the various rocks.

In short, the kind and sequence of events in Appalachian deformation accord more than usually well with those deduced from the density differences. The history of the Appalachians is similar to that of other mountain systems in the increase of folding and oscillation until the climax was reached. While all ranges do not have the same origin or history, the general agreement is worthy of note. It is also of interest to point out that the early overthrusts of the Appalachians correspond well with the faults of the later mountain systems, the Appalachian faults being more deeply eroded while the others still show their surficial aspect.

In summing up, the theory of batholithic intrusion seeks to explain the formation of the folded Appalachians by pressure from intrusions of magma. These furnished the heat and force required, were of adequate power and bulk, and accord remarkably with the varied phenomena of the system, both in space and in kind. No other theory even approaches an adequate explanation. This theory relies only on natural processes whose effects are open to observation, and it calls for few conditions that are not known to have existed and on none that are unreasonable. The basal facts of the theory have been gathered and verified

by scores of geologists and are not open to serious challenge. While the theory was framed for the Appalachians, it fits other systems reasonably well and may serve as a basis for further investigation of them. It adopts many of the great facts and processes on which other theories are based, notably those of suboceanic spread and isostasy, and forms a consistent and reasonable whole. It has a flexibility in regard to time and space possessed by no other theory. Its actuating power does not accumulate steadily and require rhythmic action, like shrinkage, nor is it exhausted in one convulsion, as in partition of a satellite. Its results are related to the heavy masses of the earth and not to meridians and parallels, so that no upsetting of earth constants is demanded. Finally, it is adequate in quantity, as few theories are.

It is not in the nature of things that this theory, or any on the same subject, should be fully proven, but it is hoped that its derivation from the Appalachian facts, its reliance on established physical principles, and its accordance with the conclusions of other sciences will gain for it serious consideration.

CONTRIBUTION TO THE HYPOTHESIS OF MOUNTAIN
FORMATION ¹

BY E. C. ANDREWS

(Presented before the Society December 29, 1922)

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INTRODUCTION

An examination of the Broken Hill district in New South Wales has suggested to the writer the advisability of attempting a tentative correlation of observations made by him during recent years within the mountain areas of Australia, New Zealand, Fiji, British Columbia, and the United States. The article presented herewith may be found to be of some assistance to those who have studied the formation of mountains.

¹ Manuscript received by the Secretary of the Society August 9, 1922.

It forms one of a series of four related papers. One of these is included in the Broken Hill Report itself.² The others deal with the origin of "Coral reefs"³ and the "Distribution of ore deposits in Australia," respectively.

DISTRIBUTION AND ARRANGEMENT OF THE PRESENT MOUNTAINS OF THE EARTH

In the present paper brief reference is made only to a few salient facts concerning the mountains which are related to the Pacific Ocean and to the ancient regions of Tethys.

The mountains of Eurasia, North America, South America, and Australia are arranged in rings or belts, which rise progressively in height in proportion to the distance traversed from the continental nuclei toward the equatorial or Tethyan region on the one hand and the Pacific Ocean on the other. These heights are referred to the nearest sea-floor or "ocean deep" as base.

In Eurasia the outer rings of the mountains are the subparallel belts of the island arcs of the Pacific and Malaysia, together with the syntactic arcs of the Himalaya, the Alps, and related ranges, such as the Pyrenees and the Elburz.

In Australia the mountains pass from the southwestern nucleus in broad and compound undulations, by way of the eastern Australian region to Malaysia and the island arcs of the southwestern Pacific.

In America the mountains pass toward the Pacific in the main from the continental nuclei in a complicated series of syntactic arcs separated by tectonic valleys. These arcs include the Rockies and its subordinate divisions, such as the Selkirks, the Cascades, the Sierra, the Coast ranges, the Andes, and related ranges.

These plateau strips of America, together with their separating valleys, are the eastern homologues of the Japanese, Caroline, Solomon, Tongan, Samoan, Fijian, Society, and other island arcs of the western Pacific.

This statement needs some slight modification, inasmuch as the American mountains have been controlled in some measure by the suboceanic mass of the Atlantic region. Recurrence is made to this point below.

The Indian Peninsula is related to the Indian Ocean in a manner similar to that of northern America with the Pacific.

Africa shows a distinct division into two parts, namely, a northern one, which is controlled by the Tethyan area, and a southern one, which shows

² E. C. Andrews: *Geology of Broken Hill*. Memoirs No. 8, Geological Society of New South Wales, 1922.

³ E. C. Andrews: Presidential address, Roy. Society of New South Wales, 1922.

an influence exerted by the associated basins of the Indian, Southern, and Atlantic oceans.

The nuclei of these great regions are wide plateaus of low vertical relief, with the exception of a few localities to be mentioned later. The main examples are the "Canadian Shield," the "Siberian Nucleus" or *vertex* of Suess, the "Scandinavian Nucleus," the Brazilian Plateau, the Southwestern Australian Plateau, India, and a portion of Africa. These regions are not broken by great gaps of tectonic origin arranged along radii spreading or diverging from the older portion of the nucleus.

The modifications suggested above are due to the existence of the high Atlantic margin of the Scandinavian Plateau, the relatively high plateau fringe to the "Canadian Shield" within Labrador, and the ghats of India. With these, perhaps, may be included the relatively high plateau blocks in the northern portion of the West Australian Plateau.⁴

All these great continental shields are low in general altitude and are encircled by broad land troughs filled with waste from the earth crests, or undulations, forming these continental shields or nuclei. Beyond the mighty plains of these lowlands and alluviated areas, namely, the savannas, prairies, and plains, sympathetic rings of plateaus form outer lines of land or earth crests. These are narrower and higher than the low-lying nuclei, and they are broken to a considerable degree by warpings and depressions which tend to be arranged along directions diverging radially from the nuclei. Outer arcs occur beyond these in turn, and they are narrower than those of the middle group; they are of much greater absolute height above the ocean bases or deeps; and they have suffered great transverse warpings and faultings arranged along lines extending radially from continental nuclei. This latter statement applies to the western portion of the Pacific rather than to that of the eastern. Examples of these transverse warpings are the separation of New Zealand, New Caledonia, Tonga, and Fiji.

A few additional notes may be supplied concerning the arrangement of the Asiatic plateaus, this continent being a type of the great land blocks of the world.

The Siberian nucleus is a low plateau diversified locally by a few high ridges. The mountain ranges of the continent are arranged in arcs whose convexities are directed mainly from the nucleus toward the Pacific and Indian oceans.⁵

⁴ Verbal communication from Sir Edgeworth David from information supplied to him by A. Gibb Maitland.

⁵ F. Bursley Taylor: Bearing of the Tertiary mountain belt on the origin of the earth's plan. Bull. Geol. Soc. Amer., 1910.

There are two related, but independent, controls for these Eurasian ranges, namely, the Pacific and the Equatorial (Tethyan or Southern). The result is an interference of controls which has given rise to a great mountain system like a vertebral column from the Stanovoi in the north-east of Asia to the great Pamir Plateau in the south. The knots or vertebræ form mountain ranges which increase in grandeur, as do also their attached ribs or ranges of varied lengths, as they are traced progressively southward through the festoons of the Stanovoi, Yablonoi, Saigon, Altai, Alai, Tian Shan, Kuen Lun, Hindu Kush, Karakoram, and Himalaya.

Each of these represents a compound earth wave or undulation, whether of interference or of outward and relatively unimpeded pulsation. The Pamir and the Himalaya are types of interference and of outward pulsation respectively.

Each of these units, such as the Himalaya, with the great Tibetan Plateau, is ornamented with longitudinal ridges or plateaus of tectonic origin arranged parallel to the main trend of the range itself. As the continental margin or ocean is approached, the mountains open in swinging nature to assume parallelism with the coast. Examples are the Stanovoi, Manchurian, Chinese, Burmese, Himalayan, Persian, and mountains of other Asiatic provinces. So also the Kurile, Aleutian, Japanese, Philippine, Malaysian, and other island arcs represent the Pacific Ocean analogues of the Himalaya or Tethyan type.

These land crests are all separated either by land troughs, sea basins, or by ocean trenches.

With progressive passage outward from the nuclei, it may be seen that the complex rings of plateaus become narrower, higher, and more discontinuous as land surfaces considered as units.

This is a generalization for Asia which it might be advisable to bear in mind in connection with the distribution of the mountains of other continents.

AGE OF THE EXISTING MOUNTAINS

Every important mountain range or arc, together with its associated land trough, is a complete earth wave and may be considered as composed of a main structure which possesses pressure ridges, or subsidiary ranges, both attached to it and arranged subparallel to it, but lying at a greater radial distance from the continental nucleus than the main ranges.

Examples are (1) the main, lesser, and sub Himalayas; (2) western Fiji, the zone of volcanic islands, the raised coral limestone islands, with volcanic or sedimentary nuclei, the eastern atolls.

The main belt of each group is relatively stable and is Tertiary or possibly even Pleistocene in part, whereas the age of the extreme outer groups is Pleistocene at least for the Pacific region. This statement refers only to the present general form and the general altitude of the island belts considered. The history prior to the formation of the present mountain forms is considered in another chapter. These greater arcs, together with their subsidiary ridges, may be separated by ocean deeps or by deep intermontane valleys (land troughs) or they may occur merely as associations of high and less high plateaus arranged in parallel zones.

These complete units are progressively stable in proportion to their proximity to the continental nucleus from the great ocean deeps.

Examples are the Society Islands with the Paumotu, Tonga with its parallel zones of volcanoes, coral islands, and ocean trenches; Fiji with Lau, New Caledonia with the Loyalties, Australia with its continental shelf and outer islets.

The works of Barrell, Berry, Bowman, Brouwer, W. M. Davis, Diller, Dutton, Gilbert, Ellsworth Huntington, Lawson, Le Conte, Lindgren, Molengraaff, Powell, Tangier Smith, Warren D. Smith, T. W. Vaughan, the Indian and the Alpine geologists, and others, all supply evidence a study of which indicates that the main mountain blocks existing today are not older than Pliocene, and that they are associated with pressure ridges in certain instances of Pleistocene age. Especially convincing in this particular are the works of the authors mentioned above for the Pacific, the Indian, the European, and the West Indian regions discussed by them.

DISTRIBUTION AND ARRANGEMENT OF PAST MOUNTAIN SYSTEMS OF THE EARTH

In a general way it may be said that existing mountains are similar and similarly situated to earlier mountain ranges. On the other hand, there are decided deviations from this general law.

In the first place, the grandest examples of mountain chains of the present day occur within or near the margins of the Pacific and the Tethyan regions.⁶ The existing mountain chains decrease in grandeur of appearance in confocal zones traced progressively from the ocean toward the continental nuclei in directions at right angles to the general movement of earth-wave pulsation.

⁶ In this connection the Pacific is considered as inclusive of Mexico, the Antillean zones, and their continuation through Venezuela and Colombia. The Tethyan area is considered as equivalent to the region named Tethys by Suess, together with its continuation to the southeast.

In the second place, the older mountain systems may be considered as having attained their most spectacular development nearer the continental nuclei than the sites of the greatest ranges of today. The order observed in the geographical distribution of mountains would appear to have been such that the oldest systems of maximum importance were developed in rings progressively nearer the nuclei under consideration in a backward review of time. In other words, there is a great and accumulating amount of evidence existing to support the belief that, with the progressive passage of time, mountains extended outward successively in space as rings from the nuclei.

In the third place, these ancient mountains were arranged in the form of arcs, which are similar in a general way to existing types; on the other hand, the older members, which have vanished from the landscape, appear to have had a sphere of influence, which extended not so far from the ancient nuclei as the present types, but the individual rings or belts affected were of much greater width than those of present and recent mountains.

A study of the continents themselves suggests the existence therein of two or more great confocal arcs of crystalline schists which mark the sites of ancient and enormous mountains due to folding. The innermost of these consists of the great continental nuclei themselves, namely, the Scottish Highlands, Scandinavia, Siberia, the Canadian Shield, the Brazilian Shield, the West Australian Shield, peninsular India, and certain parts of Africa. The second occurs beyond the curving belts of the great plains or prairies which separate the nuclei from the outer rings. In America this is indicated by the belt extending through Alaska, the Yukon, British Columbia, Montana, Colorado, Arizona, Texas, and the Appalachians, for North America, and lies beyond the great savannas following the Cordillera from Venezuela to Patagonia, for South America.

In Australia the second ring is carried through Camooweal from the Northern Territory, through western Queensland, south Australia, Broken Hill, in New South Wales, and in all probability a narrow belt in western Tasmania.

Within Eurasia this second belt appears to follow the Tethyan region, together with the general trend of the eastern coast of Asia.

The outer belt appears to pass, in the case of North America, from Alaska along the coastal region to southern California, and in South America from Colombia to Patagonia. The trends of North and South America are separated in the Caribbean region by trends that in general are east and west.

For Australia the outer arcs of schists pass through New Guinea and the New Zealand or South Pacific festoon.

It is believed by some observers that these outermost belts of schists represent Archeozoic types, but it is probable that the majority of them may be referred hereafter to periods very much later than the Archeozoic. It is to the great nuclei and to the second ring that we may look with confidence to the development of the Archeozoic folds. These nuclei and rings of schist are all separated by reciprocal valleys and plains or by land and sea troughs.

Of the most ancient it may be said, possibly, that they passed outward from the nuclei in a series of land crests and troughs, the eroded cores of which possess mainly a general tilt or inclination toward Tethys and the Pacific. The evidence of the influence of the Atlantic, Southern, and Indian oceans should be remembered also in this connection. Reference is made in another place to this extra-Pacific influence.

This growth by outward extension of rings and by decreasing intensity of folding at the nuclei or centers appears to have been characteristic of mountain formation during certain great time units, such as the Archeozoic, Proterozoic, Cambro-Ordovician, later Paleozoic, Mesozoic, and Cenozoic.

STRUCTURE OF EXISTING MOUNTAINS

COMPARISON OF RANGES

It is not many years ago that the main mountain ranges of the globe were considered to be of the fold type, and, moreover, that the age of each individual system, much as it exists today, was considerable. A statement by Gilbert,⁷ and quoted by W. M. Davis in "Explorations in Turkestan, 1905," is interesting in this connection:

"In the Appalachians corrugation has been produced by folding, exceptionally by faulting; in the Basin Ranges commonly by faulting, exceptionally by flexure."

All mountain ranges examined by the writer, considered as to their general form and height, appear to be no older than the close of the Tertiary, and to be of the plateau type, with warped or faulted margins. With regard to Gilbert's statement above, it may be remarked that the present Appalachians appear really to be variants of the Cordilleran type, the quantitative result being much less in the case of the former, whereas the folds seen in the slopes of the Appalachian plateaus, as they exist

⁷ G. K. Gilbert: Washington, 1875, pp. 61, 62.

today, represent merely the exposed core of an ancient range or set of ancient ranges whose original surfaces may well be expected to have resembled those of the Andes, Himalayas, or western Cordillera of western North America. The turmoil and tumult of mountain folding passed gradually from the continental nucleus to the ring including both the Appalachians and the western Cordillera, but at a still later stage this intensity of mountain-making had become lopsided or eccentric and had passed toward the Pacific, leaving the Orient, or Atlantic, side almost moribund, so far as folding phenomena were concerned. Nevertheless, the two are comparable, the difference being one mainly of degree. Had the Appalachians, during the closing Tertiary, been raised to heights equivalent to those of the Himalaya or of the Western Cordillera, their margins would have crept and have folded their own outwash gravels in the process. Could the core of the mighty plateau of the Himalaya be exposed to view today, doubtless it would be seen that the surface, with its faulted and warped margins, passes downward into zones of rock folding and flowage of the same age as the plateau surface.

Of the Tian Shan, Davis⁸ says that the—

“contrast between the earlier Tian Shan system and the present ranges is similar to that pointed out by Gilbert between the Appalachians and the Basin Ranges of Utah and Nevada.”

In this connection the remarks of Ellsworth Huntington⁹ concerning the Tian Shan during the Cenozoic are worthy of the utmost consideration:

“Coupled with the uplifting of the peneplain by which it was deformed into basins large and small, with intervening swells or ridges, as far as was observed, this warping does not seem to have initiated new lines of stress, but to have conformed to old ones of Tertiary age. In the old movements faulting takes place abundantly; in the new movements warping was the rule and faulting took place rarely. The Quaternary basins seem to be revivals of former basins. . . . The scale of the Quaternary warping was large, for some of the ridges, such as the main crests of the Tian Shan Plateau and of the Alai Range were raised over 10,000 feet above the bottoms of the neighboring basins.”

“Apparently, the Kashgar Basin has long been growing smaller by a process of continuous folding along the edges, and as it has grown smaller the locus of deposition of the gravels which accumulated along its edge has gradually been pushed inwards” (p. 170).

“Along the section¹⁰ the profile is essentially a very broad anticline of the

⁸ Explorations in Turkestan. Pumpelly Expedition, Carnegie Inst., 1905, p. 81.

⁹ Explorations in Turkestan. Pumpelly Expedition, 1905.

¹⁰ Tian Shan (E. C. A.).

Uinta type, as defined by Powell; where the sides are monoclines and the top is flat . . . the anticline is not strictly flat on top, but undulates. . . ." (p. 171).

From this illuminating statement of Huntington, it would appear that the Tian Shan uplift has been revived time after time, the high plateau formed in each case progressing southward and northward on each great uplift, crushing its outwash gravels in the process and yet preserving a general undulation for the plateau surface itself.

THE HIMALAYA

This great mountain system consists of a series of parallel ridges or plateaus which form the front ranges to the Tibetan Plateau, the Kuen Lun forming the buttress of the same plateau to the north. The Tian Shan and the Alai plateaus form a similar and similarly situated but less magnificent feature to the north, being separated from the great southern form by the mountain knot of the Pamir.

Godwen Austin¹¹ indicates six of these geological axes:

(1) The main central Asian axis, the Kuen Lun forming the northern edge of ridge of the Tibetan Plateau.

(2) Trans-Himalaya of Muztagh or Karakorum.

(3) The Ladakh chain.

(4) The Zaskar, or main chain, rising to heights from 20,000 to 29,000 feet. This is the range generally known as Himalaya.

(5) Outer Himalaya.

(6) The sub-Himalaya, in places very distinctly marked from the main chain by open valleys (dhuns) or narrow valleys parallel to the main axis, of the chain. This group includes the Siwaliks.¹²

"It appears, therefore, that the Himalayas grew southward in a series of stages. These stages formed sub-Himalayan pressure ridges in front of the main chain. . . . In time the deposits of the present Indo-Gangetic plain will be involved in the fold."

AMERICAN CORDILLERA

The mountains of North and South America have been ably described by a number of illustrious observers. An excellent summary of the epics of this galaxy is given in Chamberlin and Salisbury's *Text-Book of Geology*. The great labors of Powell, Daly, Dutton, Gilbert, Lawson, W. T. Lee, Le Conte, and Ransome might be mentioned in this connection.

The existing mountains are the grander revivals of individual Cenozoic uplifts exhibited as a vibratory and undulatory process extending through

¹¹ *Encyc. Brit.*, Ed. 11, vol. 13, Himalaya.

¹² P. Lake: *Encyc. Brit.*, Ed. 11, vol. 13, Himalaya.

several periods, such as the Eocene, Miocene, Pliocene, and in places the earlier part of the Pleistocene.

The land crests or plateaus formed during the earlier uplifts were reduced, possibly, to the stage of "rolling downs" or wide plains prior to the revival of uplift at later stages in the Cenozoic.

The present forms appear to be pressure ridges with flattish or undulating tops and with edges warped or faulted down to intermontane valleys of structural origin. Powell's Uinta and the Rocky Mountain front are types. The Atlantic mountains indicate a feebler response, in the form of a complete earth wave, to the same dominant control.

The western side of the Sierra, together with the land trough of the Californian Valley, affords a magnificent example of warping during the later portion of the Cenozoic. The foldings of the Pliocene and of the Pleistocene on the Californian coast are examples also of a type of structure girdling the real Pacific on the east.

EUROPEAN MOUNTAINS

These appear to be replicas, on a smaller scale, of the Asiatic forms which began with the upheaval of the Tethyan bed.

AFRICAN MOUNTAINS

These may be described as similar to those of the other continents, but their formation has not been under the direct control either of the Pacific or Tethyan regions.

AUSTRALIAN MOUNTAINS

These are plateaus relatively low in height and formed within dense rocks. The younger and less compacted rock types occur within the great plains of the center. The surfaces of the plateaus are undulating, the margins being warped and faulted. This fact is appreciated only in the regions of unfolded rock types, such as those of the Permo-Carboniferous at the Bacchus Marsh scarp in Victoria, the Trias-Jura of the Blue Mountains in New South Wales, the Trias-Jura conglomerate flanking the slopes of New England, and the Darling Downs, in New South Wales and Queensland respectively. In the closely folded Paleozoic rocks which form the general surface of the great plateaus of eastern Australia, the warping, with faulting of the margins, is not discernible with ease. Nevertheless, it is implied by the continuity of the general form of the plateau margins themselves, which are traceable through the area of horizontal rocks to the areas of slate where the rocks have been closely folded.

It is implied also by the geographical unity of the whole side of eastern Australia during Cenozoic time.

The New Zealand mountains tell a similar but more dramatic story than the more stable land blocks of Australia.

STRUCTURE OF PAST MOUNTAINS

The appearance of the surfaces of past mountains can be inferred only from a comparison of their exposed cores or stumps, on the one hand, and from the general form of existing mountains, on the other.

It is natural in this connection to understand that there is little or no knowledge to be had of ancient mountains formed of rocks with negligible dip. Districts of ancient folding only are considered in this connection.

Two things, however, are suggested at an early stage in this discussion:

(a) The Eocene and Miocene mountains, of which the present magnificent ranges of the earth appear to be revivals by vertical uplift following on long cycles of denudation, exhibit wonderful folding phenomena and evidence of igneous intrusives of plutonic type at the cores. This is observable within the Tethyan area and at the locus of the interference of the Tethyan and Pacific controls.

(b) The very old mountain systems show a remarkable development of close folding.

The areas occupied by mountains of Archeozoic and early Proterozoic time were enormous, both in length and in width. This statement appears to hold, apparently, whether the areas considered be Eurasia, America, Australia, Africa, or peninsular India.

This fact alone, at first sight, would suggest that the influence of folding in ancient time had extended over immense areas. The rock outcrops themselves of these old mountain cores also suggest an arrangement in subparallel or confocal rings somewhat as the ranges of today, due allowance being made for local variations during successive periods, such as the slow wanderings due to land-wave interference, or cusps, which has caused great deviations of strike, amounting to many hundreds of miles in length in places. This is in marked contrast with the distribution of post-Huronian mountains.

On and within the ancient nuclei of the continents the post-Huronian sediments appear to be but little folded and altered. On the other hand, the Paleozoic sediments are folded strongly in strips which are relatively narrow on the outer belts, between the Archeozoic rings, but which pass thence with gentle or negligible dip toward the continental nuclei. These Paleozoic fold areas, however, are relatively wide as compared with the rings of Cenozoic folding.

These features are illustrated well in Australia, as elsewhere.¹³

Excellent examples of the relatively narrow strips of folded sediments of the Cenozoic occur within regions embracing the Alps, the Himalaya, North America, and elsewhere.

For the Alps the close folding of the Molasse and the Flysch¹⁴ pass within short distances into the horizontal beds of the same age lying to the north in Germany and France. This feature is well illustrated also in the Himalayan region, both to the north and the south, the zone of close folding being narrow. In America, from the works of Lawson, Ransome, Tangier Smith, Le Conte, Diller, Lindgren, and others, it would appear that the very narrow zones of the folded Cenozoic along the Pacific margin pass inland into plateau and interplateau troughs, the margins being warped and faulted, while in the great plains of the center the Cenozoic lies horizontally. In Australia the edges of the coastal plateaus are warped and faulted. Low pressure ridges lie in front of these coastal and inland plateaus, but are of negligible width.

RELATION OF AREAS OF SEDIMENTATION TO MOUNTAIN RANGES

An examination of the great folded areas of the world indicates the close relationship which has existed always between areas of great sedimentation and of later mountain formation. In illustration of this point it is only necessary to mention the mountains of the Archeozoic and the early Proterozoic periods, as those also of the Appalachian, Himalayan, and Alpine regions. In some, as in the area of the Grand Canyon, the Archeozoic sediments were folded closely and subsequently denuded to the very core of the great mountain systems. The immense thickness of the sediments of the Algonkian which were deposited upon the planed surface within the Archeozoic was raised later into lofty ranges of the fold type. These in turn were removed by denudation in great measure, and through the succeeding ages received the slow and steady sedimentation of the Cambrian, Ordovician, later Paleozoic, Mesozoic, and Cenozoic periods, producing a total of many thousands of feet of sediment. During the Cenozoic this mass was lifted gently to form plateaus, the movement being revived several times without folding, as the term is generally understood.

Other regions, as the Himalayan,¹⁵ after a long period of Mesozoic sedimentation, experienced a powerful folding during the late Cretaceous,

¹³ E. C. Andrews: *Journal of Geology*, 1916.

¹⁴ P. Lake: *The Alps*. *Encyc. Brit.*, Ed. 11, vol. 1.

¹⁵ P. Lake: *Encyc. Brit.*, Ed. 11, vol. 13, Himalaya.
Also, Wadia: *Geology of India*.

with marked intrusions of a plutonic type. In the middle Eocene the great thickness of Tertiary sediments was folded. Again, in the Miocene, close folding was revived to the accompaniment of great plutonic intrusions. The Pliocene marked a plateau uplift of magnificent proportions, to the accompaniment of heavy crushing and folding along the plateau margins.

A significant fact in connection with existing mountains is that the main plateaus occur in the harder and older rocks, while the basins between them contain the softer and less altered sediments, the latter being crushed on their margins if the bordering ranges are very high, whereas they are gently bowed or warped only if the associated mountains possess but a moderate amount of relief, and that only near the plateau bases.

SOME SPECIAL FEATURES OF CENOZOIC MOUNTAINS

Before leaving the subject of the nature of past and existing mountains, it may be advisable, perhaps, to consider a few additional points in connection with the Cenozoic types.

In the first place, they are plateaus with warped margins, and they are the revivals of Eocene and Miocene examples which exhibit certain differences among themselves.

The earlier mountains may be divided into three groups, all alike, but showing great variations in the quantitative factor. One group is the Tethyan, the members of which have been formed in geosynclines between two dense landmasses during the Eocene and Miocene. The sediments laid down in these geosynclines were intensely folded and were intruded by plutonic rocks.

The second group is that whose individuals are distributed in and around the Pacific. These show signs of folding during Cenozoic time.

The third group is the similar, but less important, group bordering the Atlantic and western Indian oceans.

The inference is that the mountains of Eocene and Miocene time had been comparatively great only in the Tethyan area. Basaltic flows devastated the areas of India, western America, eastern Australia, and some other places at the same time.

The Pliocene and early Pleistocene mountains, on the other hand, were giants whose distribution was cosmopolitan. They exist today, deeply dissected it is true, but with their mighty and original profiles in an excellent state of preservation.

These mountains of the plateau type were developed not only in the unstable portions of the earth's crust, such as the Tethyan-Pacific mar-

gins and western Pacific areas, but also in those regions also of the earth which had come to be regarded as the very symbols of stability, such as peninsular India, Africa, western Australia, the Canadian Shield, the Brazilian Shield, together with the Scandinavian and Siberian nuclei. This is one of the most difficult facts for the student of mountains to explain.

It is an interesting point to note that the mountains of Africa and of India follow the trend of the coasts and have their highest points, or knots, at points corresponding to the large land turns.

This fact of mountain distribution is most significant, especially when considered in conjunction with the knowledge that these mountains existing today within the old areas of stability are much grander than their predecessors of the early Cenozoic.

RELATION OF VOLCANOES, EARTHQUAKES, AND OF IGNEOUS INTRUSIONS TO MOUNTAIN FORMATION

EARTH WAVES AND VOLCANOES

The Tethyan group of mountains overlooks sea troughs or deep alluviated land troughs, whereas the Pacific types on the west overlook the Pacific itself, but on the eastern side they overlook the Pacific in part only; for example, the Coast Range of California. The more inland groups face intermontane valleys.

Each of these earth waves presents three natural zones:

First. The outermost arcs are composed either of ocean trenches of remarkable depth or of land troughs partly alluviated. Thus the ocean trenches of the Pacific comprise the Hæckel, Richards, Bartholomew, Krümmel, Milne Edwards, Maury, Supan, Tuscarora, Challenger, Nero, Pelew, Philippine, Planet, Kermadec, Aldrich, and Tongan deeps, ranging from 24,000 to 33,000 feet in depth. The Indo-Gangetic plain, on the other hand, is a magnificent example of an alluviated land trench in the Tethyan area, but being homologous with the Pacific Ocean trenches.

Second. These mountains, estimated, according to the nature of the case, either from the alluvial plain or the ocean trench, as datum levels present great convex arcs to the ocean or to Tethys. The convexities are connected by appropriate concavities—that is, with mountain arcs whose convexities are directed toward the continental nuclei in the main. Examples of these are the Caribbean or Antillean arcs, the Alps, the Patagonian; Falkland, and South Georgian arcs, the Alaskan Knot, the Bolivian Knot, and the Bornean and Celebean arcs.

Outer arcs in each of these complex rings or earth undulations appear

to be the compound zone of earthquakes, which is apparently within the zone of more recent ridging in front of the major uplifts.

Third. Within the second zone are arranged the volcanoes which again fall into the active or extinct types, according to the zones of pressure or relative stability within which they occur. All, however, are of Pleistocene age.

A necessary modification to this statement is that the mountain rings form individual units arranged subparallel to each other and within which these arrangements of earthquakes and of volcanoes occur, not as one line only, but in as many lines as there are unstable island groups.

IGNEOUS INTRUSIONS

All students of mountainous areas, past and present, have been impressed with three facts of worldwide application:

(a) In the Archeozoic and the lower Proterozoic areas, which are those of intense folding, and in those of the narrower zones of intense folding of Paleozoic age, the amount of igneous intrusions is remarkable. In proportion to the intensity of the metamorphism evidenced, these intrusions appear to partake of the sill or lenticular form, lying between bedding and schistosity planes, especially where the latter are almost coincident with the former.

(b) In the areas of deep-seated folding of the Cenozoic sediments, and which are exposed today by denudation, a very common occurrence is the igneous intrusive of the plutonic type as bosses and related forms, with attendant dikes. The Tethyan region exemplifies this well. In regions uplifted at the same time, but not folded, namely, the arcs nearer the continental nuclei, great sheets of basic lavas were extruded without accompaniment of tuffs or explosive features.

(c) In the great plateaus formed during the Pliocene revival of mountain-making, there was a marked development later of volcanic craters on the inward side of the pressure zones or arcs of Pleistocene age.

It would seem, therefore, that the formation of great mountains is attended by the introduction of enormous volumes of igneous material within the areas affected by the folding and mountain-making generally.

The nature of this igneous manifestation is peculiar. Thus in the deepest portions of the crust exposed at the surface today the accumulation of igneous material was so great in places as to displace the sediments intruded in great measure. The igneous material appeared to have "sweated" along the more permeable beds, and to have taken on the form of sills, from which replacements took place in great part by pegma-

tites, whereas the granite, generally in the form of primary gneiss and the basic rocks, had formed "pressure" lenses and sills. In the region nearer the surface the intrusives form tongues and dikes. In the land crests near the continental nuclei, or in the more stable areas associated with the folded region, floods of basic lava appeared at the surface. During the great revivals of mountain-making, volcanoes and earthquakes were common accompaniments of the vertical uplifts and the warpings of the surface.

RELATION OF HEATING OF UNDERLYING FOLDED SEDIMENTS TO MOUNTAIN FORMATION

The Archeozoic and lower Proterozoic rocks, where exposed, are intensely altered. Sillimanite, chialstolite, andalusite, mica, and other schists result commonly from the alteration of ancient silts and shales. This suggests the action of long and continued heating under heavy load. A study of the Australian exposures belonging to similar periods suggests that the alteration is due not so much to the igneous rocks which have intruded the sediments as to an action which has the same source as the igneous intrusives themselves. This indicates that the sediments affected must have locally increased considerably in volume.

RELATION OF ISOSTASY TO MOUNTAIN FORMATION

Bowie and Burrard¹⁶ have insisted on the necessity for the consideration of the doctrine of isostasy in discussions on mountain-making.

Burrard considers that isostasy demands a vertical uplift for mountain formations. He maintains that the uplift of the Himalayas is mainly vertical, with the crushing of the Siwaliks over a zone which is only relatively narrow.

Bowie says in his discussion on mountains:

"If this mountain mass is not an extra load, then it could not have been brought from some other area to the one it now occupies. If it is not an extra load, it could not be due to horizontal thrusts operating in the earth's isostatic shell and extending far beyond the mountain 'area.'"

Both authors appreciate the fact that horizontal movements do exist in the formation of mountains, but they consider that the main agent is vertical uplift and, moreover, that horizontal movements may be incidental to a vertical uplift.

¹⁶ Bowie: *Origin of mountain ranges*.

Colonel Sir Sidney Burrard: *Geog. Jour.*, vol. lviii, no. 3.

This in turn indicates the significance of the structure of the cores of old mountain masses, where mashing of sediments is evident over the greater portion of the continental nuclei, together with the outer rings of Archeozoic age. Horizontal movements therein must have affected areas many hundreds of miles in width.

This again points to the inevitable conclusion that mountain-making, from the viewpoint of horizontal manifestations, has been slowing down from the Archeozoic to the present, with a revival in the Cenozoic of localized horizontal movement on a gigantic scale.

The question, then, naturally arises, "Why should the cores of Archeozoic mountains show mashing on the continental scale, while Tertiary ranges show local rings of mashing only?" This point is considered below.

SUMMARY AND CONCLUSIONS

It would appear from the foregoing summary of observations that the mountains, both of the present and of past periods, have spread out from the continental nuclei in arcuate form toward the Tethyan region on the one hand, and the Pacific, together with the Atlantic, on the other. The Atlantic influence became altogether subordinate to that of the eastern, or Pacific, region proper, with the progress of time.

Today the Pacific is the main center¹⁷ toward which the continents are creeping. The general result is that the continents are becoming more stable and continuous by the consolidation and the fusion, above sealevel, of mountain rings and intervening land troughs, while the Pacific also inclines toward stability, with a tendency toward contraction of area in its deeper portions.

The study of the growth of mountain ranges appears to place the hypothesis of the permanence of ocean basins and of the continental areas on a firm footing.

If the ocean basin be taken as a datum surface, it would appear that the continental masses have flowed or crept in undulations slowly—very slowly indeed—toward the larger ocean deeps. This movement has produced earth crests and troughs—in other words, rhythmic pulsations—the land crests and troughs tending to become mutually supporting through the medium of a lower zone of rock flowage. There is, however, a slight declination of the undulations toward the great ocean basins, and there is a slight tendency to translation of material thither near the surface.

¹⁷ The main exception to this is the Tethyan influence. The case of the African mountains is not considered in this note.

Combining these results, it is permissible, perhaps, to infer tentatively that the earth shell, or, indeed, its whole mass, as Chamberlin suggests, is separable into several large blocks of varying density. These blocks have the same positions today, approximately, which they possessed in Archeozoic time, but they have been growing increasingly stable and fixed—that is to say, the Pacific area is becoming more established as a definite basin than it was in Archeozoic time, and the continents also are becoming more stable, with progress of time, by fusion and welding of the old rings of land-wave growth.

In the Archeozoic the crust appears not to have been so strong as it is at present, and thus the reaction from the deeper portions of the zone of flowage toward the surface, or region of negligible pressure, was more readily attained at that period than now. Indeed, it is very difficult to conceive of a zone where definite rock flowage could occur unless there should be an avenue of relative escape from the surrounding pressures. If it be assumed that rock pressures at depth are enormous, but the proviso be made also that they are equal in every direction and alike at all points, this relative movement between great blocks appears impossible. In nature, however, a decided opportunity for escape is supplied by the negligible pressure at the earth's surface. On the assumption of a solid earth, the only opportunity for the occurrence of a zone of rock flowage at a moderate depth within the surface shell is due to the fact of negligible pressure at the surface, where the rocks are composed of brittle material of short grain and not of a coherent band or shell of elastic material of long and strong bond, such as iron or copper. And this again implies the non-existence of a zone of marked flowage in a solid earth at a depth of hundreds of miles below the surface, outside the hypothetical contacts separating the great blocks themselves. The explanation is that the strains at great depths could be distributed wholly below the surface, and hence little or no opportunity for definite rock flowage would occur.

This conception of an avenue of escape from pressure might be borne in mind by students of dynamics, whether of ordinary streams, of glaciers, of rock flowage, or of igneous emanations: otherwise the main points at issue may not only be misunderstood, but actually overlooked.

The mighty mountain ranges of the earth, together with the igneous rocks therein, are all results of this attempt at escape to the surface—that is, to the zone of least pressure.

Chamberlin's¹⁸ conception of the initial blocks of variable density

¹⁸ Chamberlin and Salisbury: *Geology*, 1906, vol. ii, pp. 126-130. On the other hand, the subaccordant depths of the oceans, in the main, indicate strongly that the earth's surface is under one main control—that is, the zone of flowage.

underlying oceans and continents, together with his general conception of a shearing shell and of igneous intrusions along shearing zones is of great assistance at this stage. The heavier blocks would tend to sink and the crests of the lighter blocks would tend to creep toward them. The nature of the pre-Archeozoic shell is unknown, but it is here assumed as relatively weak—that is, not compacted, as is the present crust of cooled igneous and metamorphic material which forms the nuclei. The sediments of the Archeozoic, which had been buried deeply, formed a zone of flowage which had connection with the surface of that period more readily than it has at present. A creeping, or “rock flowage,” toward the great ocean basins is indicated thus, and this would take place in a manner such that the flowage was reflected as undulations at the surface. These undulations were mutually supporting, the vertical relief being slight compared with the horizontal distance between the waves or undulations, as in the case of other waves of pulsation. With local relief of pressure, the deeply seated material gave off emanations or discharges which passed through the zones of strain formed and assumed the form of sills and pressure lenses between the bedding and shear planes of the sediments. With increasing strength of the crust at the nuclei, the less deeply seated zones of pressure passed outward in confocal undulations to the margins of the unstable areas—that is, to crustal masses of less strength. These undulations, or mountains and valleys, represent vertical oscillations of material, with crushing of basin margins and slight lateral motion, rather than a transference of large volumes of material over great distances.

The control of the sinking blocks underlying the Atlantic and Indian oceans is indicated by the local ridgings of the continental nuclei as at Scandinavia and the ghats of India.

To this mountain-making the injection of igneous emanations and the heating of the sinking sediments contributed considerably, but the actual transference of material was confined to zones which were relatively narrow within each earth undulation. This action appears to have determined the great folding and mashing of the earlier and middle Cenozoic.

The formation of the present series of mountain ranges would appear to be related to a general pull, by shrinkage, of the suboceanic areas, which set up undulations therefrom in the form of complex units round the margins of these suboceanic masses and which were reflected on the one hand backward to the continental nuclei through the zone of flowage, in widening undulations of decreasing strength, and on the other hand upward thence, with an undulatory surface creep toward the oceans.

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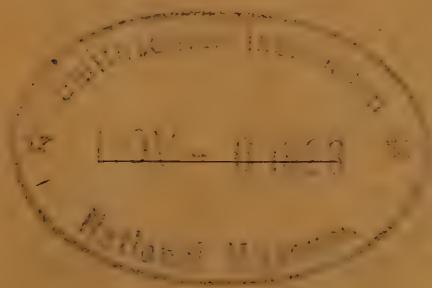
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RECENT PROGRESS AND TRENDS IN VERTEBRATE
PALEONTOLOGY *

PRESIDENTIAL ADDRESS BY W. D. MATTHEW

(Delivered before the Paleontological Society December 29, 1922)

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INTRODUCTION

In science, as in our business and personal affairs, it is profitable from time to time to look over the ground and see how much we have accomplished in recent years. The present occasion would seem to be a suitable one in which to render an account of recent progress in that branch of paleontology with which I am principally acquainted. It is not a catalogue of recent publications, nor a summary of their contents that is presented in this address, but rather a report of progress, with some suggestions as to where this progress seems to be leading us.

The foundations of paleontology, the documents on which our researches are based, consist of the collections of fossils, which are our record of the past history of life. The breadth and solidity of those foundations must determine both the size and the permanence of the structure that we may erect thereon. It is no small part of our duty as

* Received by the Secretary of the Society December 30, 1922.

architects thereof to examine carefully from time to time into the adequacy of these foundations, to condemn and sweep away such parts of our structure as appear to be insufficiently supported, flimsy or outworn. They may have served their purpose in the past as temporary outworks, trial sketches or models, or provisional scaffolding to aid in the erection of our more permanent structures; but they should not be confused with solid and stable additions, nor should they be allowed to outlive their usefulness. A critical review of our foundations and of their recent extension is the foremost and most important matter before us.

In the early days of paleontology fossil vertebrates were known from few and mostly very fragmentary specimens. Our concepts of extinct animals were built up from the study and correlation of numerous fragments, supplemented largely by the analogy of living relatives of the extinct animals. The correlations were sometimes incorrect, the analogies were always inexact and often misleading. Of the theories and conclusions based by our predecessors on these relatively scanty foundations, some have been swept away and forgotten, some have been modified in varying degree, some have been confirmed and vindicated by subsequent discovery.

The more intensive collecting of recent years, and especially the technique devised by Hatcher and Wortman for the purpose of preserving the whole of a fossil skull or skeleton, have brought in year by year a larger proportion of complete specimens of fossil vertebrates. The leading American museums are today peculiarly rich in complete and well preserved material, and the more progressive museums of Europe have likewise adopted these methods, greatly to the improvement of their collections.

It is difficult to find any basis for a quantitative estimate of the increase in our collections, or even of any particular portion of them. So far as the American Museum collections go, the Cope Collection, gathered between 1872 and 1896, covers about 25 per cent of the catalogue numbers, but is not in reality over 10 per cent of the collections in this department, as in former years many specimens were separately catalogued that would not now be considered worth individual record. The other 90 per cent was gathered during the last thirty years, and progressively more during the later decades. Perhaps it would be fair to say that 20 per cent was gathered from 1892-1902, 30 per cent from 1902-1912, and 40 per cent from 1912-1922. Other institutions would have proportions different from these. Probably in Yale University or the National Museum the proportion of material collected and prepared over thirty years

ago would be higher; on the other hand, in the newer institutions all the material is relatively recent. It is reasonable to regard the American Museum as fairly representative in this matter and to conclude that, so far as American collections go, nine-tenths of them have been obtained during the last thirty years and nearly half during the last twelve years.

Progress in foreign museums has not been so rapid, especially in Europe, where the earlier collections were more important and the World War seriously curtailed, if it did not eliminate, all scientific activities. Yet even in Europe large additions have been made since the beginning of the century and some important ones within the last decade. Judging from what I saw of the principal European museums in 1900 and again two years ago, it would, perhaps, strike a fair average to estimate that their collections have been nearly doubled since 1900.

I will try to specify the more important points in the progress of the last ten or twelve years.

PALEOZOIC REPTILES, PERMIAN OF TEXAS AND SOUTH AFRICA

On the origin of land vertebrates there is little to report in the way of new discoveries, although the researches of Gregory and Watson in respect to the relations of the earliest land vertebrates to the fringe-finned fishes have advanced our understanding of the problem; nor have any important new collections been made among the earliest land vertebrate faunas of the Pennsylvanian period. Moodie's monographic revision of the Coal Measures amphibia and reptiles¹ affords a most valuable compendium of what is known up to the present time.

In the Permian faunas, both in Texas and South Africa, there has been a great advance, both in collecting and research, continuing the activity of the previous decade. Professor Case,² of Michigan University, and the late Doctor Williston,³ at the University of Chicago, have been the leaders in this country, and have secured and described large collections from Texas and Oklahoma and greatly increased our knowledge of this ancient vertebrate fauna. The Cope Permian collections at the American

¹ R. L. Moodie: (1916.) *The Coal Measures amphibia of North America*. Carnegie Inst. Pub. no. 238.

² E. C. Case: (1907.) *Revision of the Pelycosauria*. Carnegie Inst. Pub. 55; 1910, *Articles in Amer. Mus. Bull.*, vol. xxviii; 1911, *Revision of the Cotylosauria, Amphibia, and Pisces of the Permian of North America*. Carnegie Inst. Pub., nos. 145, 146; 1913, *Permocarboniferous vertebrates from New Mexico*, *idem.*, no. 181; 1915, *Permocarboniferous Red Beds of North America, etc.*, *idem.*, no. 207; 1919, *Environment of vertebrate life in the late Paleozoic of North America*, *idem.*, no. 283.

³ S. W. Williston: (1911.) *American Permian vertebrates*. Univ. Chicago Press. And various articles, mostly in the *Journal of Geology*, 1908 to 1918.

Museum have been studied and compared with the South African faunas by Case, Gregory,⁴ Broom,⁵ Watson,⁶ and von Huene,⁷ and important collections from the Texas Permian have been obtained for the Tübingen and Munich museums in Germany. There shall be noted, also, the fine skeleton of the fin-back reptile *Dimetrodon*, recently mounted in the National Museum.⁸ The South African Permian has also been vigorously exploited by Broom, Watson, Haughton,⁹ and Van Hoepen¹⁰ and large collections made, including many finely preserved skulls and skeletons. This fauna is of peculiar interest as containing apparently the beginnings of the evolution of mammals, birds, and dinosaurs. It is significant that it is regarded as the fauna of an arid or desert region, rather in contrast to the fluviatile or littoral facies represented by the Texas Permian.

The third great area for Permian vertebrates, the Dvina River, in Poland, has not, so far as I know, been seriously exploited since the work of Amalitzky, twenty years ago, nor has anything been added to Fritsch's pioneer work in Bohemia.

With all that has been done, we really know very little as yet of the Permian land animals. The period was a most important and critical one in the evolution of land life, for it witnessed the first great expansion of land vertebrates and the origin, probably, of mammals, birds, and the principal orders of reptiles, including dinosaurs. What we know best is the river-delta fauna of the Lower Permian in Texas, a series of plains or desert faunæ of Upper Permian age in South Africa, and probably a similar facies in Poland; a small Permian swamp fauna in Bohemia, and a few items from other regions. These must represent but a small proportion of the variety and scope of land life of the Permian world. How imperfect a picture it gives may be judged by supposing that our knowl-

⁴ W. K. Gregory: Various articles in Bull. Amer. Mus. Nat. Hist., 1908 to 1922; 1913, Journal of Morphology.

⁵ R. Broom: (1908-1922.) Numerous articles in Bull. Amer. Mus. Nat. Hist., Proc. Zool. Soc. London, Ann. South African Museum, etc.

⁶ D. M. S. Watson: (1912-1922.) Numerous articles in Ann. Mag. Nat. Hist., Proc. Zool. Soc. London, Trans. Roy. Soc. London, Geol. Mag., etc.

⁷ F. Von Huene: (1922.) Osteologie des *Dicynodon* Schädels, Pal. Zeitsch., V, 58-71; 1913, Skull elements of Permian Tetrapoda, Bull. Amer. Mus. Nat. Hist., vol. xxxii, 315-386; 1912-1913, Anatomischer Anzeiger, 42 Bd., s. 98, 472; 43 Bd., s. 389, 519.

⁸ C. W. Gilmore: (1919.) A mounted skeleton of *Dimetrodon gigas*. Proc. U. S. Nat. Mus., vol. 56, pp. 525-539, pls. 70-73.

⁹ S. H. Haughton: (1915-1918.) Ann. S. African Mus., vol. xii, containing descriptions of the paleontological material of the S. African Museum and Geol. Surv. S. Africa; 1919, Review of the reptilian fauna of the Karroo system of South Africa. Trans. Geol. Soc. S. Afr., vol. xxii, pp. 1-26; 1920, On the genus *Ictidopsis*. Ann. Durb. Mus., vol. ii, part v; 1921, On the reptilian genera *Euparkeria* Broom and *Mesosuchus* Watson. Trans. Roy. Soc. S. Afr., vol. x, pp. 81-88.

¹⁰ Van Hoepen: (1915.) Ann. Transvaal Mus., vol. v, nos. 1, 2.

edge of the modern land vertebrates were similarly limited, to the animals of a South African desert, a Texas delta, and a swamp in central Europe, with a few odds and ends from elsewhere. The zoogeographer would be bold indeed who propounded theories of distribution and migration based on data so limited, and it is to be feared that his conclusions would bear but little relation to the realities. While it is thus necessary to emphasize the limitations of our knowledge, it is but fair to say that it is vastly greater than it was a decade or two ago. The number of genera on record is not so greatly increased, but our systematic and anatomical acquaintance with the characteristic types is more than doubled.

TRIASSIC REPTILES AND AMPHIBIANS OF GERMANY

Turning to the age of reptiles, we have in the Triassic the least known chapter, so far as America is concerned, and very little has been added to this chapter in the last decade. What little has been accomplished in this direction is due to the energetic prospecting of Dr. Case and contains promising prospect for the future, as well as a few but very interesting additions to the Triassic faunæ.¹¹ In Europe, however, the recent discoveries of Triassic dinosaurs at Halberstadt and Trossingen in Germany and the discovery of a complete skeleton of a South African Triassic dinosaur have given an adequate basis for the study of these primitive dinosaurs and appreciation of their real relations to the specialized dinosaurs of the later geologic periods. Especially is the discovery by von Huene, in new excavations at Trossingen during the past two seasons, of a series of a dozen or so more or less complete dinosaur skeletons likely to be of great scientific value. Scarcely less important is a large quarry of skulls and skeletons of the great Triassic Labyrinthodont *Mastodonsaurus*, in the Black Forest region by Professor Wepfner, and the discovery of complete skeletons of the very peculiar reptile *Placodus*, whose teeth were found long ago in Germany and supposed to be the pavement-teeth of a fish allied to the rays. This fine skeleton is being studied by Doctor Drevermann, of the Senckenberg Museum.

JURASSIC DINOSAURS OF UTAH AND EAST AFRICA

The two outstanding features of progress in Jurassic land reptiles are the great dinosaur quarry worked by the Carnegie Museum near Jensen, in the Vernal Valley, Utah, and the Tendaguru dinosaur collections from German East Africa secured for the Berlin Museum. So far as I can

¹¹ E. C. Case: (1922.) Carnegie Inst. Pub. no. 321.

judge from the record maps of the Jensen quarry, which I had the privilege of inspecting through the courtesy of Mr. Douglass, the material secured there is greater in quantity and finer in quality than the sum of all that has been obtained hitherto in America. The preparation of this huge collection will be a labor of many years, however it be arranged; but as a result we may look forward confidently to more than doubling our present knowledge of Morrison dinosaurs.

The memoirs by Gilmore¹² on the carnivorous and armored dinosaurs in the National Museum, chiefly of the Morrison fauna, are of the highest authority and importance and his restudy of the Potomac fauna¹³ of Lower Cretaceous age shows that it is not the Morrison, as formerly supposed, but of decidedly later age. The Tendaguru collection is likewise an immense task in preparation, and when I saw it in Berlin, two years ago, it was far from being completed, after more than ten years' work. It provides a fairly complete skeletal knowledge of some half-dozen types of dinosaurs¹⁴ and fragments of a few others, representing a fauna similar in broad lines to the Morrison fauna, nearly similar in its adaptive facies, and approximately of the same age, but inhabiting a different continent, and of the highest importance in giving some really adequate data as to the faunal distribution at that epoch. It is too early yet to draw conclusions, but my impression from a superficial review was that the Tendaguru and Morrison faunas showed a very close adaptive similarity, but were not so closely related as they seemed. It is, fortunately, possible to correlate the Tendaguru dinosaurs exactly through marine faunas in interdigitating formations. This in turn aids greatly in the correlation of the Morrison fauna, and Schuchert has shown¹⁵ that there is strong reason to place it rather at the end of the Jurassic than at the beginning of the Cretaceous. This conclusion is further supported by Gilmore's new evidence as to the relations of the Potomac fauna.

¹² C. W. Gilmore: (1920.) Osteology of the carnivorous dinosauria in the U. S. Nat. Mus., Bull. 110, U. S. Nat. Mus.; 1914, Osteology of the armored dinosauria in the U. S. Nat. Mus., Bull. 89, U. S. Nat. Mus.; see also 1909, Osteology of *Camptosaurus*; 1915, Osteology of *Thescelosaurus*, and other articles in Proc. U. S. Nat. Mus.

¹³ C. W. Gilmore: (1921.) Fauna of the Arundel formation of Maryland. Proc. U. S. Nat. Mus., vol. lix, pp. 581-594, pls. cx-cxiv.

¹⁴ W. Janensch: (1914.) Uebersicht ueber die Wirbelthierfauna der Tendaguru-Schichten. Archiv. f. Biontologie, III, 79-110; also pp. 217-261. Ueber *Elaphrosaurus* u. s. w., Sitzber. Gesell. naturf. Freunde, 1920, pp. 225-235.

W. Branca: (1914.) Die Riesengröße sauropoder Dinosaurier vom Tendaguru, u. s. w. Archiv. f. Biontologie, vol. iii, pp. 71-78.

Pompeckj: (1920-1923.) Personal communications.

E. Hennig: (1912.) Am Tendaguru; also various articles in Sitzber. Gesell. naturf. Freunde, 1912-1922.

¹⁵ C. Schuchert: (1918.) Bull. Geol. Soc. Am., vol. 29, pp. 245-280.

CRETACEOUS DINOSAURS OF ALBERTA, MONTANA, AND NEW MEXICO

It is in the Cretaceous dinosaurs that we can record the greatest progress in the last ten or fifteen years. It is not so long ago that our practical knowledge of Cretaceous dinosaurian faunas was almost confined to one horizon and to one small area. Substantially, it was the Lance fauna that we knew, and to what extent the fragmentary fossils recorded from other formations and other areas were really distinguishable from those of the Lance was a subject of acrimonious debate. Today we have extended the scope of our geographic knowledge as far as central Alberta to the north and New Mexico to the south, and have been able to distinguish four well separated geologic zones, each represented by a fauna known from a series of more or less complete skeletons. The earliest of these faunal zones is the Saint Mary's of the Milk River district in Montana; the second and best known is the Belly River of the Red Deer River in Alberta; the third is the Edmonton of the same region, and the fourth, the Lance of Wyoming and Montana. The great collections secured from the Belly River by the American Museum, the Ottawa, Toronto and Edmonton museums in Canada, and the Field Museum in Chicago are still being prepared and studied, but it is already evident that it was a surprisingly large and varied fauna, of which the Lance was but a remnant, consisting of a few highly specialized survivors.¹⁶

Another interesting phase of recent progress in this group is the probable difference in faunas widely apart geographically and in different climatic zones. The splendid specimens secured by Charles H. Sternberg in the last two seasons in the San Juan basin of New Mexico appear to represent a fauna widely different from any of the three great northern faunas. Their true correlation has yet to be determined by a more exact study of the fauna and stratigraphy, but Mr. Sternberg's latest work, performed under heavy handicaps, opens up an important new field for dinosaur collecting and is the last of a long series of important finds made by him during the last fifty years. A fine skull and much of the skeleton of a gigantic Ceratopsian has been secured by the American Museum; other important specimens are still in his hands and in the Upsala Museum in Sweden.

¹⁶ B. Brown: (1912-1917.) A series of papers in Bull. Am. Mus. Nat. Hist.

H. F. Osborn: (1917.) Bull. Amer. Mus. Nat. Hist., vol. xxxv, pp. 733-771.

L. Lambe: (1914-1920.) Numerous articles in Mem. Geol. Sur. Canada, Ottawa Naturalist, Trans. Roy. Soc. Canada, etc.

W. A. Parks: (1919-1922.) Series of articles in Univ. Toronto Studies, Trans. Roy. Soc. Canada, etc.

THE DINOSAURS NOT A NATURAL ORDER

The dinosaurs are now generally recognized as not a natural order of reptiles, but a composite group, including two distinct and rather distantly related orders.¹⁷ Dinosaurs correspond in a way to pachyderms among mammals, once considered a natural order, but now recognized as an assemblage of animals superficially alike, owing to parallel adaptation, but not really related. It is in this sense that the term "dinosaurs" should henceforth be used and not as a natural order of reptiles. The two orders are the Saurischia, including Marsh's two groups of Sauropoda and Theropoda, and the Ornithischia, or Orthopoda, the Predentata of Marsh. The first group includes the gigantic amphibious Dinosaurs, the great carnivorous Dinosaurs and their slender, swift-running allies, and the more primitive Triassic dinosaurs. Orthopoda include the Iguanodonts and duck-billed Dinosaurs, the horned Dinosaurs, and the armored Dinosaurs. All these are distinguished by a horny beak or bill and a more bird-like arrangement of the pelvic bones, and have a certain degree of affinity to primitive birds, whereas the Saurischian order has a corresponding relation to primitive crocodiles. The fine memoirs by von Huene on various Triassic reptilia,¹⁸ by Gilmore¹⁹ on the carnivorous and armored dinosaurs, by Osborn on *Camarasaurus*,²⁰ and a series of descriptive papers by Brown, Lambe, Parks, and others are the most important published contributions in this field.

CENOZOIC MAMMALS OF WESTERN AMERICA

In the field of Tertiary mammals progress has been made at many points. The great series of Tertiary faunas in this country has been improved all along the line. Collections from each horizon have been greatly increased; many new or little known species are now represented by complete skulls and skeletons. Careful intensive stratigraphic work in the fossil fields and more exact records of all specimens enable us to define more accurately the limits and succession of faunas and evolution

¹⁷ F. Von Huene: (1909.) Skizze zu einer Systematik und Stammesgeschichte der Dinosaurier, Centralbl. f. Min. Geol. u. Pal., J'g., 1909, s. 12-22; 1914, Natürliche System der Saurischia, idem, 1914, s. 154-158; 1914, Ueber die Zweistämmigkeit der Dinosaurier u. s. w., Neues Jahrb., B. B. xxxvii, s. 577-589.

¹⁸ Von Huene: (1912-1916.) Series of memoirs and shorter articles chiefly in Palæontographica; 1910-1914, Geol. u. Pal. Abhandl.; 1920-1922, Acta Zoologica; 1909-1922, Neues Jahrbuch and Centralbl. f. Min. Geol. u. Pal., etc.

¹⁹ See page 8, footnote 12.

²⁰ H. F. Osborn and C. C. Mook: (1921.) *Camarasaurus*, *Amphicælias* and other Sauropods of Cope. Mem. Amer. Mus. Nat. Hist., n. s., vol. iii, pp. 247-387. pls. ix-lxxxv.

of phyla. A great advance has been made in the Lower Eocene and Paleocene faunas, the former representing, as I see it, the true beginnings of the Tertiary mammalian succession in this country, while the latter, whatever its precise geologic position may prove to be, is essentially the culmination and close of a Cretaceous mammal fauna whose earlier evolutionary stages are wholly unknown to us, either because they inhabited upland areas, where their remains were not preserved, or because they lived in some other region whose Cretaceous land faunas have not yet been discovered.²¹

In the Lower Eocene the most remarkable discovery is the *Diatryma*, a gigantic ground bird resembling the *Phororhachos* of the South American Miocene, but not related to it and standing apart in a group by itself.²²

In the Oligocene Sinclair²³ has inaugurated an intensive stratigraphic-faunal study of the typical White River badlands that will serve as a foundation for comparison and correlation much more exact and accurate than has been possible hitherto. A remarkable fossil quarry opened by the Denver Museum²⁴ in the Chadron formation of Colorado has yielded already a large series of well preserved skeletons and appears to contain still vast numbers.

In the Lower Miocene the great collections of the Carnegie Museum from the Agate fossil quarry have been described by Holland and Peterson in three fine memoirs,²⁵ and the excellent series of *Moropus* skeletons obtained by the American Museum from the same quarry provide a complete knowledge of this extraordinary animal. Large collections have also been obtained from the Lower Miocene for the Yale, Amherst, and Field museums.

The later Miocene and Pliocene faunas are represented in the Snake Creek quarries in Sioux County, Nebraska, which have been worked

²¹ W. D. Matthew: (1913, 1917.) Bull. Amer. Mus. Nat. Hist., vol. xxxii, p. 307; vol. xxxvii, pp. 569, 831; 1914, Bull. Geol. Soc. Amer., vol. 25, p. 381; 1921, Am. Jour. Sci., vol. ii, p. 209.

²² W. D. Matthew and W. Granger: (1917.) The skeleton of *Diatryma*. Bull. Amer. Mus. Nat. Hist., vol. xxxvii, pp. 307-326.

²³ W. J. Sinclair: (1921-1922.) Four articles in Proc. Am. Phil. Soc., vols. lx and lxi.

²⁴ J. D. Figgins: (1921.) Ann. Rep. Colorado Mus. Nat. Hist., p. 16.

²⁵ O. A. Peterson: (1909.) Revision of the Entelodontidae. Mem. Carnegie Mus., vol. iv., pp. 41-158, pls. liv-lxii; 1910, Description of new carnivores from the Miocene of western Nebraska, ibid., pp. 205-278, pls. lxxiv-lxxxv; 1920, The American Diceratheres, ibid., vol. vii, pp. 399-476, pls. lvii-lxvi.

W. J. Holland and O. A. Peterson: (1914.) Osteology of the Chalicotheroidea. Mem. Carnegie Mus., vol. iii, pp. 189-406, pls. xlviii-lxxvii.

chiefly by the American Museum.²⁶ While the two great fossil quarries mentioned above contain complete skulls and skeletons of a limited number of large animals—three or four kinds in each—the Snake Creek quarries contain chiefly fragmentary material of a great variety of animals, no less than 50 genera being on my list at present. They are river-channel pockets and are now known to belong to three distinct faunal zones.

Perhaps the most interesting out of a multitude of new forms from these quarries are the upper tooth of an anthropoid primate, *Hesperopithecus*, the first of this group from the American Tertiary, and the complete skeleton of *Pliohippus*, the earliest one-toed stage in the evolution of the horse. Discovery by Troxell of fine skeletons of *Pliohippus*²⁷ and of a Tertiary type of Mastodon in the Pliocene of South Dakota, and by Gidley of a large Pliocene fauna in Arizona, should also be mentioned.

The series of later Tertiary faunas discovered by exploring parties from the University of California, on the Pacific coast and in the Great Basin provinces, are a most important addition, as they are almost wholly new fossil fields.²⁸ The material as yet discovered is largely fragmentary, but a considerable series of faunas has been differentiated.

In the Pleistocene the great outstanding discovery is the La Brea asphalt quarries near Los Angeles, remarkable for the numbers, the variety, and the fine preservation of the specimens. The discovery of this unique series makes it possible to describe the more characteristic forms from series of dozens, or even hundreds, of complete skulls with proportionate numbers of skeleton bones.²⁹

PRIMATES AND MAN

The most widely interesting field of paleontological research is that

²⁶ W. D. Matthew and H. J. Cook: (1909.) Bull. Amer. Mus. Nat. Hist., vol. xxvi, pp. 361-415.

W. J. Sinclair: (1915.) Proc. Am. Phil. Soc., vol. liv, pp. 73-95.

W. D. Matthew: (1918.) Bull. Amer. Mus. Nat. Hist., vol. xxxviii, pp. 183-229.

H. F. Osborn: (1918.) Mem. Amer. Mus. Nat. Hist., n. s., vol. ii, p. 28; Amer. Mus. Novitates, no. 37.

²⁷ E. L. Troxell: (1916.) Am. Jour. Sci., vol. xlii, pp. 335-348.

H. F. Osborn: (1918.) Equidæ of the Oligocene, Miocene, and Pliocene of North America, iconographic type revision. Mem. Amer. Mus. Nat. Hist., n. s., vol. ii, p. 162, pls. xxviii-xxx.

²⁸ J. C. Merriam and others: (1910-1922.) Univ. Calif. Geol. Publ., numerous contributions.

²⁹ F. S. Daggett: (1918.) Notes on Pleistocene fossils from Rancho La Brea. Los Angeles Co. Mus. Hist., Sci., and Art; Dept. Nat. Sci., Misc. Publ.

J. C. Merriam and others: *Ut supra*.

W. D. Matthew: (1913.) Amer. Mus. Jour., vol. xiii, p. 291; 1916, *ibid.*, vol. xvi, pp. 45, 469.

which deals with the geologic history and evolution of our own race, and in this field there have been a series of discoveries and researches in recent years of the highest importance.³⁰

First among these I may place the discovery of complete skeletons of Neanderthal man; the skeleton of Chapelle-aux-Saints, so admirably described by Marcellin Boule;³¹ the two skeletons of La Ferrassie, soon to be described fully by the same distinguished authority, and a series of less complete but important finds in Germany and other Central European States. These discoveries have given a very clear and definite concept of the Neanderthal race, as a species clearly distinct from our own, characterized by a series of well defined physical peculiarities, nearer in many particulars to the anthropoid apes, but clearly not a direct ancestor of our own species.

The fragmentary skull and jaw found in 1911 near Piltdown, in Sussex, likewise represents an extinct species of man, as different from the Neanderthal man as from our own race. Although corresponding in its nearer approach to the anthropoid apes, it probably is not directly ancestral.³²

Another remarkable skull, discovered at Broken Hill, in Rhodesia, while not of high antiquity, is regarded as representing a survival of the Neanderthal race in South Africa. The Talgai skull from Queensland, rather doubtfully associated with the Pleistocene fauna of Australia, is considered as representing a proto-Australian type of man.

The sum of these discoveries is to impress strongly on the mind the probability that our own species is but one out of several human species which lived and flourished and competed one with another during the Pleistocene period; our own species, perhaps through its higher social adaptability, being at last supreme, and sole survivor at the present day.

³⁰ The literature on fossil primates and the evolution of man is very voluminous. A number of excellent critical reviews of the subject by Osborn, Gregory, Boule, Keith, Sollas, Giuffreda-Ruggeri, Leche, Arldt, and others cite and discuss the chief contributions. The most important recent contributions on Tertiary primates are the following:

W. K. Gregory: (1920.) Structure and relationships of *Notharctus*. Mem. Amer. Mus. Nat. Hist., n. s., vol. iii, pp. 49-243, pls. xxiii-lix.

H. G. Stehlin: (1912-1916.) Säugethiere der Schweiz. Eocän, 7 Teil, Abh. Schweiz. paläont. Ges., vols. xxxviii and xli.

G. E. Pilgrim: (1915.) New Siwalik primates and their bearing on the question of the evolution of man and the Anthropoidea. Rec. Geol. Surv. India, vol. xlv, pp. 1-74, pls. i-iv.

W. K. Gregory: (1916.) Studies on the evolution of the primates. Bull. Amer. Mus. Nat. Hist., vol. xxxv, 1921, pp. 239-355; Origin and evolution of the human dentition, Baltimore. Williams and Wilkins.

³¹ M. Boule: (1911-1913.) L'Homme Fossile de Chapelle-aux-Saints, Ann. de Paléont., vols. vi-viii; 1921, Les Hommes Fossiles.

³² A. S. Woodward, G. Elliott Smith, Arthur Keith, G. S. Miller, W. P. Pyecraft, and others, on Piltdown skull.

Yet it appears probable that through crossing and intermixture some of the blood of one or more of these extinct species of man still survives here and there among our own race and may yet be recognizable when the application of mendelism to systematic osteology and paleontology is more fully understood and applied, and also when our collections of the remains of fossil man are so extensive as to admit of such applications. Whatever may be the prospects of getting anywhere along this line, it is quite clearly demonstrated by these recent discoveries that the problem of the ancestry of our race—of the evolution of man—is in reality a much more complex and difficult one than had been assumed either by the exponents or opponents of evolution. It is not one missing link that we have to find, but many. Each of the discoveries I have cited is a "missing link"; but we can not be satisfied with merely answering the challenge of the ignorant, and each discovery serves as a spur to further search.

A remarkable recent discovery is that of a true anthropoid primate in the Lower Pliocene of this country. While the single upper molar which Osborn has named *Hesperopithecus*³³ does not prove the precise affinities of the animal, there is no reasonable doubt in the minds of those who have studied the original specimen that it is one of the higher Anthro-poidea. The discovery of such a type was not wholly unexpected, as the writer and Mr. H. C. Cook, in describing the Snake Creek fauna in 1909, pointed out that certain badly preserved teeth might perhaps be anthropoid, and that the character of the associated fauna made such a discovery reasonably possible. Nevertheless it was not considered likely, as the formation had been diligently and repeatedly prospected in subsequent years without success.

FOREIGN RESEARCHES AND DISCOVERIES, MISCELLANEOUS CONTRIBUTIONS

Paleontological research in other parts of the world is much less advanced than in North America and Europe, but, in addition to the few discoveries already mentioned, several other important results of exploration have already been secured. In the West Indies a more or less systematic search for fossil vertebrates has been made by the American Museum, the Museum of Comparative Zoology and the National Museum.³⁴ and considerable well preserved material secured from the Pleis-

³³ H. F. Osborn : (1922.) Amer. Mus. Novitates, no. 37.

W. K. Gregory and Milo Hellman : (1923.) Amer. Mus. Novitates, no. 53.

³⁴ W. D. Matthew : (1919.) Proc. Amer. Phil. Soc., vol. lviii, pp. 161-181.

H. E. Anthony : (1918.) Mem. Amer. Mus. Nat. Hist., n. s., vol. ii, pp. 331-435, pls. lv-lxxiv.

G. S. Miller : (1916.) Smiths. Miscell. Coll., vol. 66, no. 12 ; 1922, idem, vol. 74, no. 3.

tocene of Cuba and Porto Rico, with fragmentary data on the Pleistocene fauna of Hispaniola and Jamaica. The especial interest of these insular faunas lies in their source and paleogeographic bearings. South America affords an immense field for exploration, but since the death of Florentino Ameghino there is but little progress to record. The explorations begun by the Field Museum will, it is hoped, initiate a new period of advance in our knowledge of the paleontologic history of this continent.

In Africa considerable reconnaissance work has been done at various points, but beyond the Tendaguru and Karroo discoveries already noted, the only finds which can be noted here are the Cretaceous dinosaurs discovered by Strömer in the Libyan desert.³⁵ These are of quite a remarkable type—Sauropods and a peculiar carnivorous genus—the fauna possibly having descended from the Wealden fauna; but careful comparative study is still needed.

In India Doctor Matley has obtained an interesting Cretaceous dinosaur fauna from the Deccan, but only preliminary notices of it have as yet been published.³⁶ The chief advance in Indian paleontology is the admirable stratigraphic and faunal work of Pilgrim in sorting out and correlating the heterogeneous group of faunas hitherto known as the Siwalik fauna.³⁷ The splendid collections of these faunas recently secured by Barnum Brown for the American Museum deserve special mention, as also the discovery of Oligocene and Eocene faunas in Baluchistan and Burma by Cooper, Pilgrim, and Cotter. The gigantic "*Baluchitherium*," of which parts of the skeleton were discovered by Cooper,³⁸ is perhaps the largest known land mammal. Borissiak has reported what seems to be the same animal in Russia, under the name of *Indricotherium*,³⁹ and last summer the American Museum secured a complete skull, nearly five feet in length, in Mongolia.⁴⁰

The results of the American Museum explorations in Mongolia are probably the most important discovery of the last decade. Central Asia

³⁵ E. Strömer: (1914, 1917.) Wirbelthier-Reste der Baharije-Stufe. Abh. Kgl. Bay. Akad. Wiss., xxvii, 3^e Abh.; xxviii, 3^e u. 8^e Abh.

³⁶ C. A. Matley: (1922.) Personal communications.

B. Brown: (1920-23.) *Ab lit.*

³⁷ G. E. Pilgrim: (1912.) Vert. Fauna of the Gaj Series. Mem. Geol. Surv. India, vol. iv, no. 2, pp. 1-84, pls. i-xxx; 1913, Correlation of the Siwaliks with Mammal Horizons of Europe. Rec. Geol. Surv. India, vol. xliii, pp. 264-326, pls. xxvi-xxviii.

³⁸ C. Forster Cooper: (1911.) *Paraceratherium bugtiense*, a new genus of Rhinocerotidæ. Amer. Mag. Nat. Hist., vol. viii, pp. 711-716, pl. x; 1913, *Thaumastotherium* [corr. to *Baluchitherium*] *osborni*, a new genus of Perissodactyles. Ibid., vol. xii, pp. 376-381.

³⁹ A. Borissiak: (1915.) Rhinoceros de la Taille d'un Mammoth. (*Indricotherium*, new genus.) Geological Messenger, vol. 1, pp. 131-134 (Russian text only).

⁴⁰ H. F. Osborn: (1923.) Amer. Mus. Novitates, no. —. (In press.)

has hitherto been a *terra incognita* to the vertebrate paleontologist, and the finding of rich and extensive fossil fields in the Gobi Desert with Cretaceous, Eocene, Oligocene, and Pliocene formations, each yielding considerable faunas and finely preserved specimens, in the first season's exploration, promises to open up a completely new field in vertebrate paleontology.⁴¹ Other fossiliferous horizons will probably be discovered by further explorations, and the history of the land vertebrates of the great central Asiatic continent in the Mesozoic and Cenozoic eras will be placed on record in considerable detail.

In the cellars and storage racks of many museums, both in this country and abroad, are important collections of fossil vertebrates acquired many years ago, but never prepared or described. The labor and expense of preparing, studying, and describing this material to make it of use to science is as valuable a contribution as though it were fresh from the field. A considerable part of the work in the National Museum and some in the American Museum has dealt with specimens collected long ago for Marsh and Cope. Recently the Yale Museum has made a vigorous and highly successful campaign to prepare and describe the great fossil collections left to that institution by Professor Marsh. A series of articles by Lull, Troxell, and Thorpe in the *American Journal of Science* testifies to the importance of these additions to our knowledge.

Two very valuable and authoritative memoirs by Doctor Teilhard de Chardin should be noted in this connection. In one the classic Cernaysian fauna at the base of the French Eocene is admirably described and illustrated from the collections in the Paris Museum.⁴² The relations of this fauna and correlation with the Paleocene faunas of this country are now at last based on adequate data. Of scarcely less importance is Père Teilhard's memoir on the carnivora of the Phosphorite fauna, also based on the unrivaled collections in the museum at Paris.⁴³

A third important memoir from the Paris Museum, sumptuously illustrated and admirably presented by the Director, Marcellin Boule,⁴⁴ describes the fine collections from the Pleistocene of the Tarija Valley, in Bolivia, in the Paris Museum.

⁴¹ W. Granger and C. P. Berkey: (1922.) *Amer. Mus. Novitates*, no. 42; 1923, *Ibid.*, no. 77.

⁴² P. de Chardin Teilhard: (1921.) *Mammifères de l'Eocene inferieur francais. Annales de Paléont.*, x, pp. 171-176; xi, pp. 1-108, pls. i-viii.

⁴³ Teilhard: (1915.) *Les Carnassiers des phosphorites de Quercy. Annales de Paléont.*, ix, pp. 100-195, pls. xii-xx; 1920, *Sur quelques primates des phosphorites de Quercy. Idem*, x, pp. 2-20.

⁴⁴ M. Boule and A. Thevenin: (1920.) *Mammifères Fossiles de Tarija, Mission Scientifique Crequi-Montfort. Soudier*, Paris.

Finally, I must not omit to mention a series of great synthetic studies by Osborn, dealing with the later Tertiary Equidæ, now published;⁴⁵ the evolution of the Titanotheres, completed but not yet published, and the evolution of the Proboscidea, still in progress; the practical completion of the splendid monographs on the Santa Cruz Miocene faunas by Scott;⁴⁶ Winge's monograph on the Brazilian Edentata;⁴⁷ and a remarkable series of brilliant text-books by Othenio Abel, of Vienna.⁴⁸ There are several other excellent text-books that deserve particular notice, but time will not allow even a mention of them here.

CONCLUSIONS AS TO PROGRESS OF RECENT YEARS

In the foregoing outline of progress I have been concerned chiefly with discoveries of new material, of new records, because it is the scanty and fragmentary nature of the evidence that is the chief limit to research in vertebrate paleontology and the chief source of error in our conclusions. In the phrase of a French reviewer, vast floods of ink have been spilled on problems of correlation, of phylogeny, of paleogeography, where a few questionable fragments of fossil vertebrates formed the salient points of evidence. When in some instances an adequate fauna was discovered, the problem was promptly and conclusively settled, the flood of ink suddenly ceased to flow, and deep calm settled over the controversy.

The fundamental progress achieved appears, therefore, to be measurable better in terms of collections than of researches. I do not altogether agree with a distinguished Columbia professor who declared not long ago that paleontologists had no business to reason on or draw conclusions from their specimens, but should content themselves with describing and illustrating them.⁴⁹ Nevertheless, I do think we should distinguish far more sharply between provisional and tentative conclusions based on scanty and fragmentary data and those which are really proven by adequate evidence.

⁴⁵ H. F. Osborn: (1918.) *Equidæ of the Oligocene, Miocene, and Pliocene*. Amer. Mus. Mem., n. s., vol. ii, pp. 1-217, pls. i-lviii.

⁴⁶ W. B. Scott and W. J. Sinclair: (1903-1912.) *Rep. Princ. Exped. Patagonia*, vols. iv-vi.

⁴⁷ A. H. Winge: (1915.) *Jordfundne og nulevende Gumlere fra Lagoa Santa*. E. Museo Lundii, Kjöbenhavn, 1915.

⁴⁸ O. Abel: (1909.) *Ban und Geschichte der Erde; Das Zeitalter der Reptilien hereschaft*, Vienna; 1912, *Grundzüge der Paläobiologie der Wirbelthiere*, Schweitzerbart. Stuttgart; 1914, *Die Vorzeitlichen Säugethiere*, Fischer, Jena; 1919, *Die Stämme der Wirbelthiere*, Ver. wiss. Verleger, Berlin-Leipzig; 1920, *Lehrbuch der Paläozoologie*, Fischer, Jena; *Methoden der paläobiol. Forschung Urb. u. Schwarzenberg*, Berlin-Wien; 1922, *Lebensbilder aus der Tierwelt der Vorzeit*, Fischer, Jena.

⁴⁹ T. H. Morgan: (1916.) *A critique of the theory of evolution*, pp. 24-27.

So far as the older and better known fields of vertebrate paleontology are concerned, the progress of the past few years has been in the way of consolidating and confirming what had been tentatively sketched out by earlier workers. In the newer fields we are reaching out and securing the first fruits of exploration—the evidence which will confirm or disprove hypotheses and guesses that hitherto have had free rein.

SOME TRENDS OF MODERN WORK

In the field of paleogeography I may call attention to three publications treating the subject from diverse or opposite viewpoints:

Matthew: Climate and evolution, an essay of some 318 pages;

Arlt: Paleogeographie, a treatise of 2 ponderous tomes;

Case: Paleogeography of the Permian, a quarto volume of moderate dimensions.

It is commonly said that paleogeographic problems should be decided only after marshaling all the evidence in every branch of zoology, past and present, as well as of geology and physiography, that can be brought to bear on it. This is what Doctor Arlt has endeavored to do in his great treatise. I do not hold that view, for it appears to me that unless evidence is thoroughly understood and critically sifted as to its weight and its real significance, it is of no value; and it is obviously impossible for human intelligence to attain a thoroughly critical grasp of so vast a field. On the other hand, the evidence in any one branch, if interpreted rightly, will lead to correct conclusions, and if the conclusions drawn in one field conflict with those drawn in another, it can only be because one or the other is wrongly interpreted. It is not a question of balancing the evidence. If it does not *all* point one way, then there is some mistake in the interpretations placed on the facts. The problem then lies in finding out what is the fallacy and in which field it lies; and whether the evidence in several fields has been vitiated by the same fallacy. It is only thus that one can arrive at true conclusions in problems of this sort. To attempt to decide them by the balance of evidence, as one would settle a problem in taxonomy, is more likely to put one wrong than right.

Doctor Case's volume is of interest as placing a novel and much broader significance on the term paleogeography, making it almost equivalent to what might be called paleoecology. He has little to say in this volume as to the question of continental outlines, so commonly discussed as though it were the whole of the subject, but is concerned chiefly with the habitat of the animals, its nature and changes, and the physical geography of Permian North America.

There has been for the past two decades a tendency among vertebratists to keep more closely in touch with stratigraphic geology. The comparative anatomist, especially in setting forth the evolution and specialization of structures, tends to arrange his material in categories and sequences that show the evolution of structures and organs, but are of course structural and not genetic sequences, as the animals are all contemporaneous. The paleontologist, however, is dealing with true genetic sequences, exact or approximate; with the evolution of species and genera of animals, not merely with illustrations of how certain structures may have evolved. The time relations of his specimens must be known exactly and carefully considered. This has been always to the forefront in invertebrate paleontology. Much of the early research in vertebrate paleontology, however, was by men who were comparative anatomists rather than geologists, and the fragmentary material with which they had to deal made a thorough practical acquaintance with comparative osteology the first essential to its correct identification and study. It is no less important today on account of the complex structure of the vertebrate skeleton; but an inevitable consequence is a certain tendency to take the anatomist's viewpoint and study too much the evolution of structures and not enough the actual sequence in time of the animals themselves. The corrective of this tendency is a closer union with the geologists, and in the founding of our Society it was hoped and expected that this would result. So far as I can see, the course of American paleontology in the past two decades has demonstrated the wisdom of this action. The exact records of specimens and more careful stratigraphic studies have enabled us to define horizons and differentiate faunas in much more precise and correct detail; and, with the far larger collections and more complete specimens, the records are adequate to trace in many cases the evolution of species and not merely of structures. The earlier writers on evolution did not attempt this. Gaudry and Hæckel, Rüttimeyer and Kowalewsky, Huxley and Cope, demonstrated from the paleontologic record the evolution of structure. Depéret and Schlosser, Osborn and Scott, and many others have perceived and pointed out this weakness in our evidence and have attempted to trace the true phyla. But it is only recently that the evidence has been adequate to place such attempts on a really sound and permanent basis, and indeed most of our work in this line is still tentative and provisional. Nevertheless, we may expect to see these beginnings extended year by year, and the old structural phylogenies elaborated by the previous generation, and scoffed at with some justice by critics as a vast "schwindelbau," replaced by the veritable records of the phyletic

history of races of animals. In so far as this is accomplished, Professor Morgan's strictures on paleontological evolution,⁵⁰ which are aimed really at the old methods, not at our modern standards, will be no longer justified. Paleontologists, with the facts before them as to what actually did take place in the evolution of a race of animals, may claim the right to reason and draw conclusions from these data as to the methods and causes of the transmutation of species.

On the anatomical side of paleontology, the far greater completeness of our material in recent years has stimulated comparative researches of high quality, apparent in many of the memoirs I have cited and in a series of memoirs by Gregory, Watson, Broom, Williston, Case, and many others.

Taxonomic researches and revisions have by no means been neglected, but I can mention only one of the many completed or in progress, the revision by Miller and Gidley of the super-generic groups of rodents, in which, for the first time, the fossil representatives of this order have received adequate treatment in a comprehensive revision.

In looking over the apparent trend of recent advances I am impressed with the honest and conscientious endeavor everywhere apparent to provide a broader and more secure foundation of evidence for our researches by much more extensive collections, more complete specimens, and more exact records. We have tried to get into closer touch with stratigraphic geology on one side, with comparative anatomy and zoology on the other. We have, on the whole, I think, kept fairly clear, considering the great increase in our collections, of the temptation to multiply species correspondingly, the besetting sin of the systematist; and, although the Mendelian school of zoologists will have naught to do with us, we have succeeded, I think, in making very good use of the data and viewpoints that they have emphasized and incorporating them satisfactorily into our own scheme of things.

⁵⁰ See footnote 49.

SOME STRUCTURAL FEATURES OF THE PLAINS AREA OF
ALBERTA CAUSED BY PLEISTOCENE GLACIATION ¹

BY OLIVER B. HOPKINS

(Read before the Society December 30, 1922)

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INTRODUCTION

Some anomalous structural features in the Great Plains area of Alberta have been known for a long time, but in recent years they have come into considerable prominence because of the prospect of commercial oil pools being associated with them. The study of one of the most conspicuous of these supposed uplifts, together with the result of wells recently drilled in the vicinity, indicate fairly conclusively that there has been no uplifting of the formations in the area, and that the abnormally steep dips and local folds and faults are the result of the thrust of the great ice-sheet which moved southward over this area in Pleistocene time.

The object of this paper is to demonstrate, if possible, two points, namely:

(1) That the intense deformation of the beds observed at Mud Buttes and similar localities is entirely superficial and without deep-seated significance and in no way connected genetically with tectonic disturbance of the region.

(2) That the abnormal surficial disturbance of the strata was caused by the movement of the continental ice-sheet against conspicuous pre-glacial hills.

¹ Manuscript received by the Secretary of the Society January 15, 1923.

The writer acknowledges with pleasure the cooperation of Dr. J. S. Stewart in the development of the ideas herein set forth and his help in the preparation of this paper.

DESCRIPTION OF REGION

The area in which the abnormal structures are found is in the plains region of east-central Alberta (see accompanying sketch, figure 1). Ab-

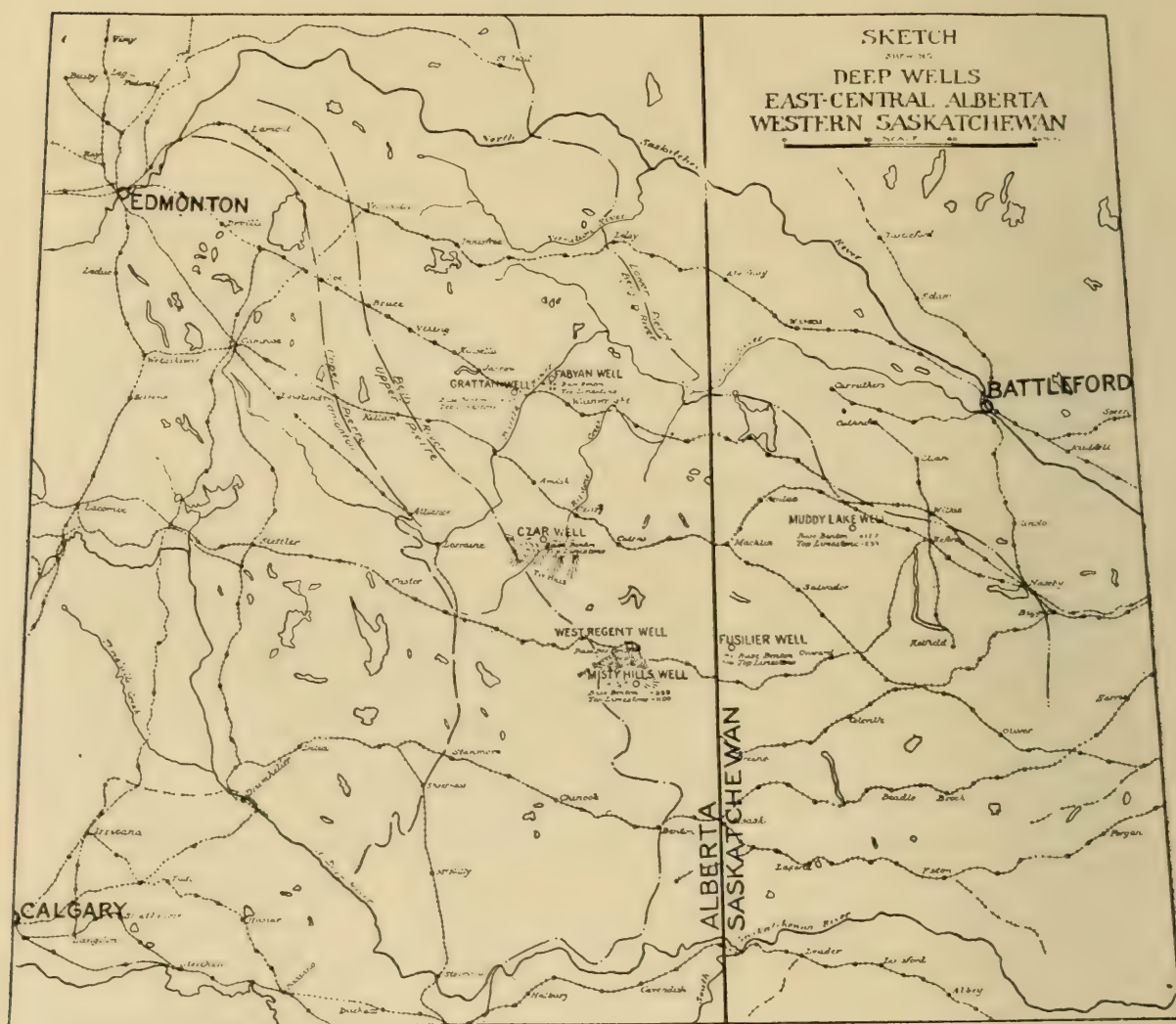


FIGURE 1.—Deep Wells of east-central Alberta, western Saskatchewan

normal dips are found at many places in that region; but the complex structures, to be described later on, are found in two principal groups of hills, namely Tit Hills and Mud Buttes. The former are located 10 miles south of Czar and the latter 9 miles south of Monitor. In most of the hills of the region abnormal dips are in evidence, due either to

slumping or other causes, whereas exposures in the valley generally show the strata to be flat-lying, in conformity with the general dip of the region.

In this part of the Great Plains are found here and there groups of hills, such as those named above, and other similar ones, such as Misty Hills, Neutral Hills, etcetera, which rise a few hundred feet above the generally flat, treeless, but well grassed plain.

Cretaceous formations underlie the surficial deposits of the plain to depths of 2,000 to 3,000 feet. The outcropping strata in the immediate vicinity of the hills, here described as showing abnormal deformation,



FIGURE 2.—*General View of Tit Hills*

belong in every case to the Belly River formation. With the exception of the abnormal dips in the few hills referred to above, all the evidence points to uniform but gently dipping beds over the whole area; but as the formations are soft, exposures poor, and the width of the outcrop great, it is difficult to work out detailed structure.

MUD BUTTES

As the conclusions herein set forth were derived largely from a brief study of the Mud Buttes, it is proper that they should be described in some detail.

The Mud Buttes are situated 9 miles south of Monitor, a station on a branch of the Canadian Pacific Railway, and cover parts of sections 19 and 20, township 33 north, range 4, west of fourth meridian.

They form a compact group of hills about one mile long by one-half mile broad which rise a few hundred feet above the plains. Their superior altitude has caused them to be eroded into typical bad-land topography, exposing admirably the strata of which they are composed.

The strata belong to the Pale Beds, the upper division of the Belly River formation, of Middle Montana age, and consist of a series of interbedded sands, sandy clays, and lignitic clays with ironstone bands.

The beds show a prevailing dip of about 30 degrees to the north-north-east and a general strike varying from north 80 to 110 degrees east. At many places the strike and dip is modified by slumping, which adds to the apparent intensity of the deformation.

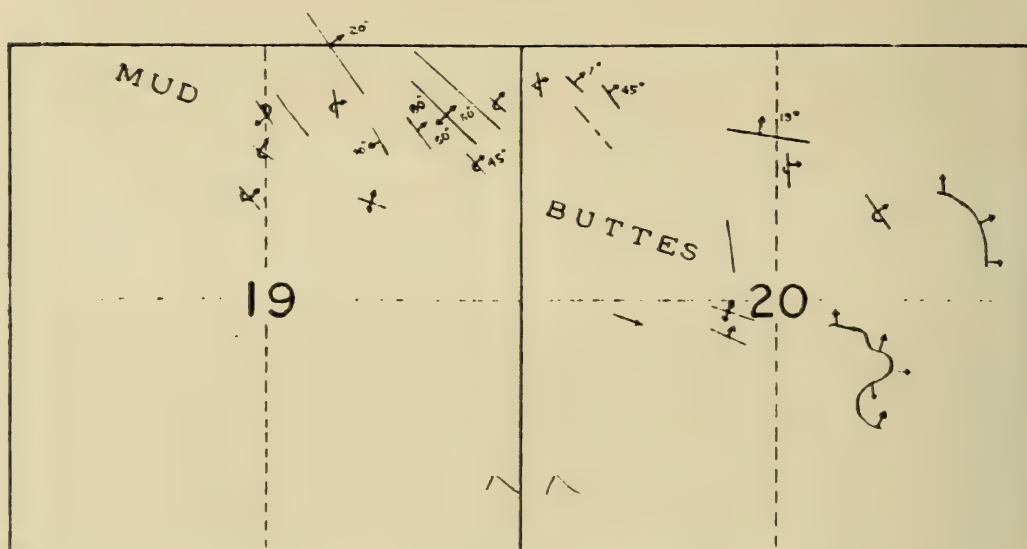


FIGURE 3.—Sketch Map showing geologic Structure of Mud Buttes

Sections 19 and 20, township 33 north, range 4 west of 4th meridian, Alberta.

The same series of beds are repeated several times by the miniature folds and thrust faults which run through the hills in a general east-west direction. Sufficient work has not been done to map the details of the structure accurately, and as figures 5-10 illustrate the intensity of the faulting, folding, and crumpling I shall not attempt to describe it in detail. That the same series of beds are duplicated is obvious from a study of the outcrops and from the fact that only the upper division of the Belly River formation is involved, as stated above.

A noteworthy feature of this supposed uplift is the general absence of dips in any direction other than to the north. The fact that the hills show only prevailing north dips caused them to be considered the north limb of an uplift; but there are no complimentary east, south, or west



FIGURE 4.—*View of Mud Buttes from the Southeast*



FIGURE 5.—*Near View of Part of Mud Buttes*
Showing small overthrust folds.

dips. This fact in itself makes the shape and extent of the supposed uplift conjectural.

EVIDENCE OF SURFICIAL NATURE OF DISTURBANCE

There are many lines of evidence enumerated below, which lead to the conclusion that the intense disturbance of the strata in this area is surficial in character; in fact, the only evidence of uplift is the presence, locally, of steeply dipping, faulted, and folded strata. Such evidence is conclusive so far as it does not run counter to all other evidence, as it appears to do in this case.

The supposed uplifts are located in every case on the outcrop of the Belly River formation, and in no case do they cause either narrowing or widening of the outcrop, nor do they bring to the surface strata older than those normal to the area. Furthermore, several subdivisions of the Belly River formation are recognized in this area and are found apparently in their normal sequence, in a regular descending series eastward and ascending series westward, thus indicating the absence of folds of appreciable size, such as we should expect from the intensity of the deformation displayed at Mud Buttes. If the observed dips were other than surficial, certainly the normal distribution of formations would be disturbed, as a 30-degree dip has been observed over a distance of one-half mile at Mud Buttes. If this dip should continue without duplication of strata for $1\frac{1}{4}$ miles, the entire Cretaceous section would be exposed, whereas only the upper division of the Belly River is found.

Turning now to the structural information from well logs; the best line of evidence is derived from four wells, which include the Muddy Lake, Fusilier, West Regent, and Misty Hills wells. These are roughly on a line from northeast to southwest, down the dip, and the last two are in immediate proximity to Mud Buttes.

The base of the Colorado Shale, which is the most reliable datum present, shows a dip of 5 feet per mile from the Muddy Lake to the Fusilier well, and $6\frac{1}{2}$ feet per mile from the Fusilier to the Misty Hills well. Thus the Misty Hills well, which is on one of the supposed uplifts, instead of being structurally higher is in reality as low as would be expected from the regional structure of the area. Furthermore, from the West Regent well, which is on the north side of the supposed uplift, to the Misty Hills well, a distance of 11 miles, there is a dip to the south of 7 feet per mile, which is also normal for the area. The significance of this is obvious from the fact that the Mud Buttes are half way between these wells.

Thus, from the evidence available, we are led to the conclusion that



FIGURE 6.—*Close View of Mud Buttes*
Showing intense folding and faulting.



FIGURE 7.—*Close View of Mud Buttes*
Showing intense folding and faulting.

there is no uplift at Mud Buttes, as has been supposed by many geologists who have visited the area.

Regarding Tit Hills, the other center of supposed uplift, the evidence is similar and equally convincing that no local uplift is present. A well was drilled on the north side of these hills, on the supposed uplift, and instead of finding a structural high found the formations at their normal depth. Thus the base of the Colorado found at 154 feet above sealevel at Fabyan, 40 miles to the north, is found here at 233 feet below sealevel, showing the normal southward dip of $9\frac{1}{2}$ feet per mile.

The larger group of hills to the south of Mud Buttes, named Misty Hills, have not been deformed to the same extent as Mud Buttes, but this may be explained readily as due to the greater resistance of their much larger mass. Considerable dislocation of the normal attitude of the strata is found in these hills, however, and this is attributed in part to the movement of the ice-sheet and in part to slumping.

The nature of the disturbance of the beds at Mud Buttes and Tit Hills is not such as could be attributed to the development of gentle folds. The intensity of the folding and faulting, if due to deep-seated forces, could only have resulted from (a) tremendous local uplift, (b) or from intense lateral compression, such as produces great overthrust faults. We have already seen that there is no intense local uplift present, as no old rocks are brought to the surface. Furthermore, there has been no regional movement that could have produced these local deformations. The region is singularly devoid of structural disturbance; the only feature of note which appears to disturb the generally flat-lying and gently dipping beds is a slight change in strike from southwest to south or slightly east of south. This, however, is a broad regional feature which can best be explained as due to warping of the former Cretaceous basin along broad lines. Such a slight amount of differential movement, necessary to produce the observed change in strike of these flat-lying beds, could not be called upon to explain such intense local disturbances as found here.

Thus the distribution of the formations and the broad consideration of the structure, together with the confirmative evidence from deep borings, lead to the conclusion that the disturbance of the strata is of surficial origin.

EVIDENCE OF THRUSTING FORCE

The similarity of the structure observed in Mud Buttes to that developed in the foothills belt of Alberta, where the limestone ranges of the



FIGURE 8.—*Near View of Mud Buttes*
Showing complicated detailed structure.



FIGURE 9.—*Near View of Mud Buttes*
Showing complicated detailed structure.

Rockies have overridden the Cretaceous, leads naturally to the supposition of similar causes, but operating on a smaller scale. The similarity is quite marked in the following respects:

(a) The disturbance of the formations leading to crushing and crumpling is more intense on the north side of the hills—that is, on the side from which the thrust was applied.

(b) Folds and faults have been developed at right angles to the direction of the thrust—that is, in a general east-west direction.

(c) Thrust faults are the dominant structural features, and such anticlines as are formed are commonly thrust faulted on their southern limb.

(d) Thrust faulting has led to the formation of small blocks which dip generally to the north—that is, in the direction from which the thrust was applied.

The analogy is so close that we are forced to look for a thrusting force from the north-northeast, whether it is granted that the deformation is surficial or not.

DEVELOPMENT OF COMPLEX STRUCTURE BY MOVEMENT OF ICE-SHEET

If the surficial nature of the disturbance is granted, the surficial nature of the force and its direction leads naturally to the assumption that the thrusting force was the great ice-sheet because it was the only competent force. It might be questioned whether the movement of the ice-sheet was a competent force, as it is not usually conceded such power for performing work. However, it is unquestionably the most potent surficial force and probably the only one that can be called upon to explain such results.

The hills present in the area today were undoubtedly hills in Pleistocene time and formed obstacles to the forward movement of the ice-sheet. The ice piled up against and finally overrode the hills. As the pile of ice increased, the pressure against the north side of the hills probably caused the soft shaly strata to buckle and fold, accompanied by movement along some horizontal bed of soft material, thus developing a horizontal thrust plane. As this continued inward toward the center of the hill, a subsidiary fault would develop along the small buckles, thus causing the thrust faults observed at Mud Buttes (see figure 10). When the blocks thus formed had been rotated to such a position that the pressure was more or less at right angles to the bedding, instead of parallel to it, the strata would be capable of transmitting the thrust, causing the extension of the flat thrust plane and the further development of other blocks. In this way the complex structure observed was probably developed.

The absence of marked infolding of glacial material is due to the fact that glacial deposits are largely found in the valley and that the hills were probably truncated by the movement of the ice-sheet across their tops. Thus the hills as seen today may be only the roots of former hills of which the strata comprising them have been jumbled up and their tops cut off by the planing action of the ice-sheet.

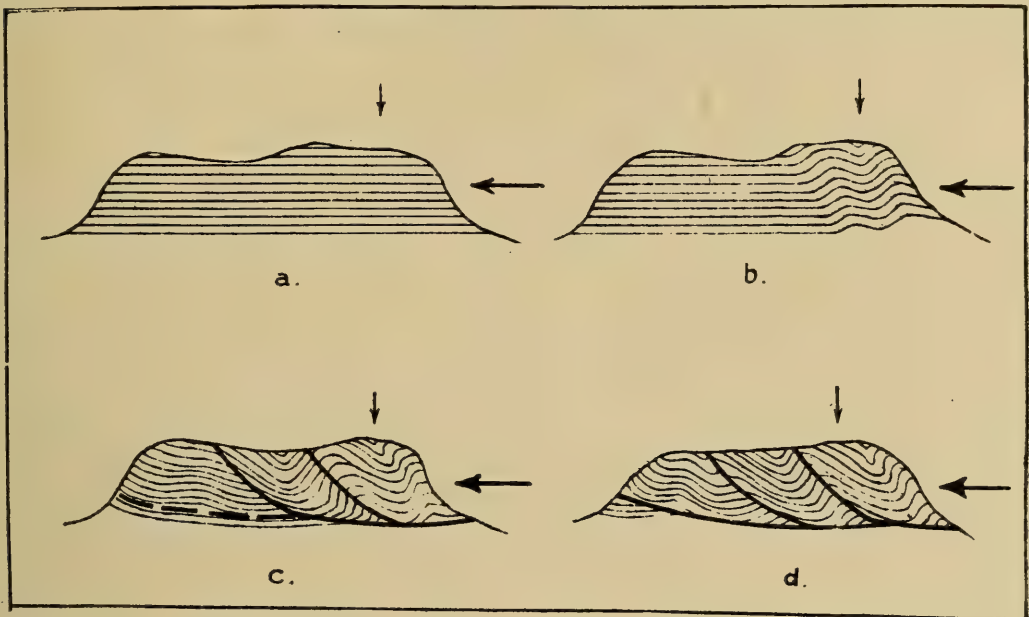


FIGURE 10.—*Development of Structure of Mud Buttes*

Sketches *a, b, c, d* represent hypothetical stages in the development of the complex structure of Mud Buttes

SUMMARY

Briefly stated, then, there is a belt in eastern Alberta where the upper member of the Belly River formation outcrops, and in some of the hilly portions of this belt the soft incompetent strata are intensely folded without bringing to the surface the older more deeply buried beds. There is no disturbed region outside of this belt from which stresses, such as are indicated by the folding at Mud Buttes, might have been transmitted. There is no apparent change in the width of the outcrop of the Belly River formation in the vicinity of these intensely folded areas such as might be expected to result from such folding.

Nowhere in eastern Alberta do the river sections exhibit or indicate folding, but wherever the dip is determinable the strata are nearly horizontal, dipping at the rate of only a few feet per mile toward the southwest. Corroborative evidence of this gentle dip toward the southwest is found in the records of deep wells drilled in the region.

The conclusion seems justified that the folding and faulting at Mud Buttes and similar localities is surficial and does not affect the underlying formations.

What force could produce intense deformation of surface beds without affecting the underlying ones? Slumping will not account for it, as the folding shows too much regularity in strike and dip and involves the entire mass of the hills. The only competent force that can be called upon to explain surficial disturbance of the strata is the continental ice-sheet which moved southward over these hills in Pleistocene time.

FUSION OF SEDIMENTARY ROCKS IN DRILL-HOLES ¹

BY N. L. BOWEN AND M. AUROUSSEAU

(Presented before the Society December 30, 1922)

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INTRODUCTION

In drilling for oil the taking of core samples of the beds penetrated is becoming a common practice. With the rotary drill the rock cuttings are ordinarily swept out by a vigorous forced circulation of sludge in the hole, but it has been found possible in many cases to modify the procedure in such a way that a core of moderate length can be obtained. The usual bit is dispensed with and a length of ordinary drill pipe with teeth cut at the end is substituted. This is rotated at the bottom of the hole, and under favorable circumstances it cuts through the rock and furnishes a cylindrical core. The presence of the core prevents the circulation of water to the bottom of the hole; indeed, a wooden plug is sometimes inserted in the top of the core barrel to guarantee this condition. With the free circulation of water thus cut off, the heat produced by the friction of boring may be sufficiently localized to raise the temperature of the rock very considerably; in fact, it is not uncommon to obtain

¹ Manuscript received by the Secretary of the Society February 15, 1923.

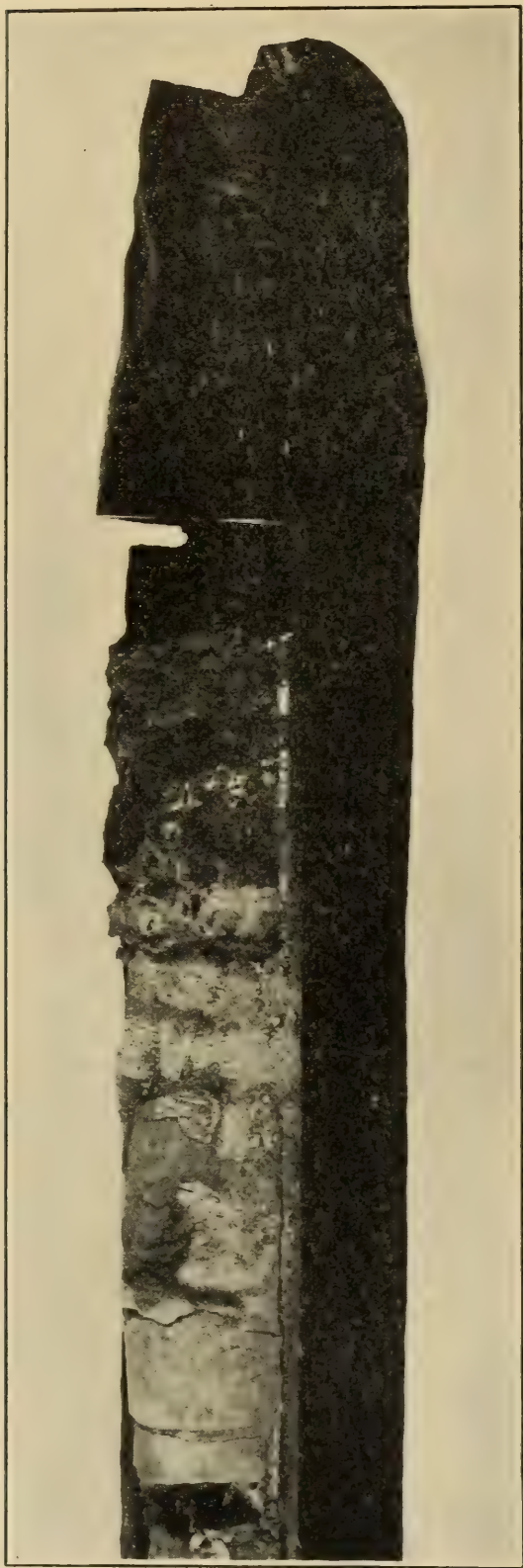


FIGURE 1.—Core Barrel from Montezuma Well Number 1

Showing deformation and twisting of the tip. It is sectioned immediately above the tip to show nature of contacts. The lower part was filled for a length of about one foot with a dark slag, which shows dark in the sectioned part, but has been removed from the tip for laboratory study.

more or less complete fusion of the rock. Fused cores have been examined by competent geologists and pronounced the result of fusion of the sedimentary rock in place,² but in spite of this fact some operators are unwilling to accept their findings and believe that natural igneous material was encountered.

A particular good example of a fused core was obtained in a well being drilled in California under the supervision of Prof. Bailey Willis. This, together with another not so well preserved, was sent by him to this Laboratory, and the results of our examination are set forth in the present paper. We are greatly indebted to Professor Willis for the opportunity of studying this material and for information regarding the conditions under which it was formed.

The better core comes from a hole near Suisun, California, known as Montezuma well number 1. At a depth of 4,350

² A. F. Rogers: Seventh Annual Report, State Oil and Gas Supervisor, vol. 7, no. 9, California State Mining Bureau, March, 1922, p. 6; C. S. Ross, Bull. Am. Assoc. Petroleum Geol., vol. 6, 1922, pp. 372-374.

feet, when in Eocene shale, so called, a core was taken after the method outlined above. The driller reports that the barrel was rotated at a speed of about 25 revolutions per minute and estimates the pressure resting on it at about 20 tons. The first 21½ feet of the core were penetrated in 20 minutes, but the rest, amounting to one foot, went very slowly and required about 40 minutes. It may be safely assumed that this latter period corresponds with that during which significant heating and softening of the drill occurred.

When the core barrel was raised it was found that the end of it had plainly been softened and twisted, and that it was filled for a length of about one foot by a dark, slaggy plug. Above this came the unaltered sediment, locally much twisted and contorted by the motion of the drill, but elsewhere still retaining its banding little disturbed. The tip of the core barrel and the part immediately above it, sectioned so as to exhibit the nature of its contents, are shown in figure 1.

MICROSCOPIC CHARACTERS OF THE CORE MATERIAL

The excellent state of preservation of the core makes it possible to arrive at some definite conclusions regarding the changes that have occurred. The unchanged sediment is banded in alternating layers of coarse and fine material, with the coarse markedly predominating. The coarser layers are made up of arkose and the finer layers are more definitely shale-like. Under the microscope the arkose is found to consist largely of angular to subangular grains of the following minerals in order of abundance: quartz, plagioclase (mainly Ab_2An_3), and microcline, with minor amounts of biotite, muscovite, and indefinite claylike matter. The shaly layers are made up largely of finer grains of the same minerals with a moderately greater amount of the claylike matter.

The rather friable and little compacted material of the unchanged sediment gives place abruptly to the dark slaggy mass of the fused portion. The only change to be noted as the fused part is approached is that a few platy crystals of tridymite have been formed in the arkose.

The characteristic feature of the fused portion (see figure 2) is the presence in it of glass. In the glass are embedded the undissolved grains of the original minerals, which may vary in amount from about one-half of the whole mass to a very small fraction of it. In places, then, the rock has been converted almost completely to glass, in which case the mass is light colored and of a pale yellow in thin section. As the extent of fusion diminishes, the glass becomes darker and more nearly opaque. The refractive index of the glass varies somewhat, but is never far from

1.53. Such selective action during fusion as is in evidence is mainly connected with the size of grain rather than with the nature of the material. The residual undissolved grains are the larger grains of practically all the minerals present, and the ready getting together of the finer grains to effect mutual fluxing has evidently been the important factor in facilitating fusion. Quartz and plagioclase are the more persistent,

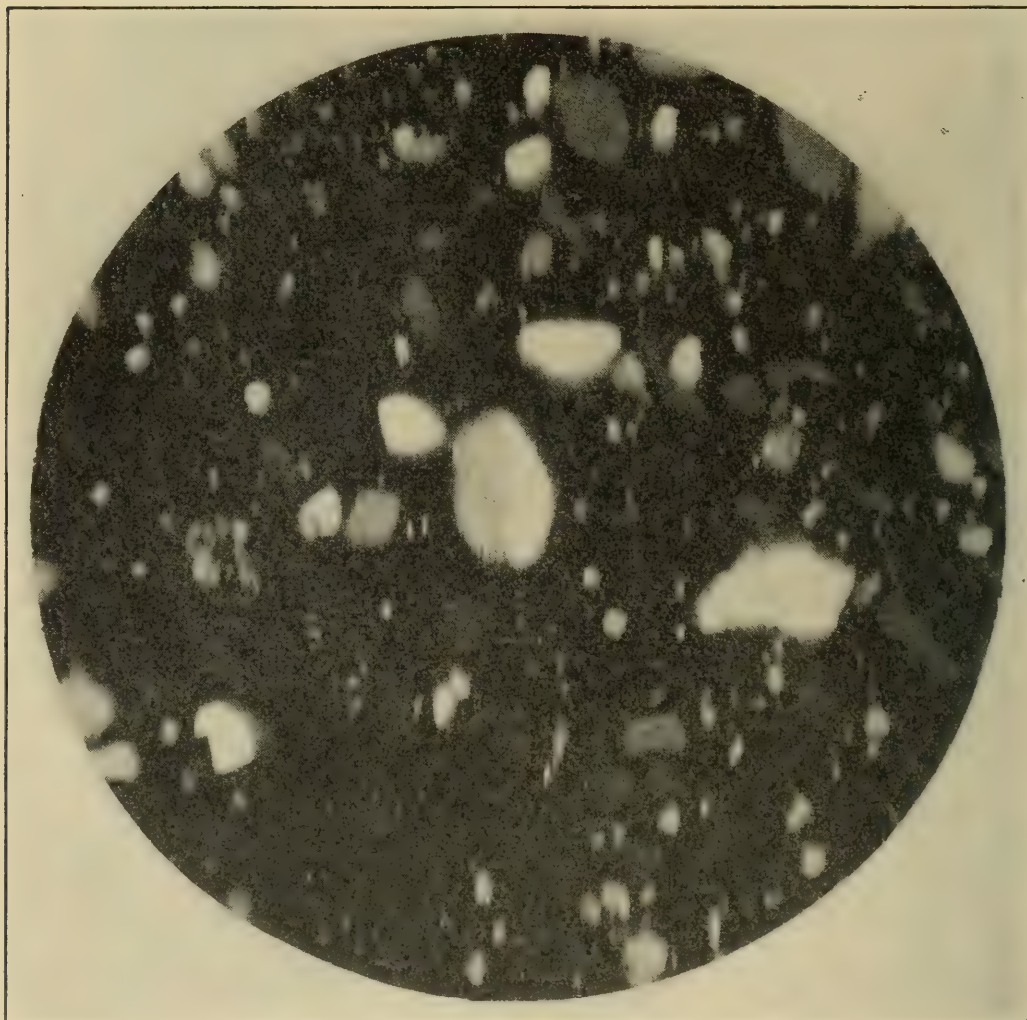


FIGURE 2.—*Thin-section of fused Core, Montezuma Well Number 1*

Crossed nicols. The dark areas are glass, the bright patches undissolved grains of quartz and plagioclase. Twinned plagioclase at center.

as they are the larger grains, but the quartz is apparently not more persistent than plagioclase. It is not impossible, however, that the very fine so called clayey matter may be intrinsically more fusible. Occasional small fragments of metallic iron from the pipe are to be found in the glass.

In most of the glass there is a moderate amount of recrystallization. The separated crystals are not definitely identifiable, but appear to consist largely of minute needles of sillimanite. Close to the iron pipe there is a fairly conspicuous development of fayalite in small but definitely determinable grains of very high birefringence and minimum refractive index about 1.83.

CHEMICAL CHARACTER OF THE CORE MATERIAL

The general appearance of the core and the microscopic characters of its material leave little room for question as to the fusion of sediment in place. Any lingering doubt is completely dispelled by a chemical study of the fused and unfused portions.

Samples for analysis were obtained by selecting representative fragments of the broken part of the fused plug and by taking a chisel cut about a foot long in the unfused material immediately above the plug.

The ordinary methods of silicate analysis, as advocated by Hillebrand and Washington, were employed, except that in the determination of metallic iron in the fused portions recourse was had to the method given by Treadwell and Hall, which involves treatment of the sample with mercuric chloride solution and subsequent titration of the dissolved iron in the presence of manganous sulphate.³

The determination of metallic iron in the presence of iron oxides can not be carried out with great precision by any method adaptable to our problem. The results are to be regarded as close approximations. In the presence of metallic iron the determination of ferrous iron by Pratt's method is unreliable. The core contains only a slight amount of metallic iron, and therefore the oxide determinations, both by Pratt's method and as total iron oxides, were in very close accord. A series of determinations was made and the figures given are the average of these determinations. As the average values for FeO plus metallic iron considered as FeO and total oxides considered as FeO differed only by 0.03 per cent and as the fusion took place in the presence of metallic iron, it must be considered that there is no ferric iron present. Moreover, we have been unable to detect magnetite in the fused product. At the same time it can not be proved by chemical means that ferric iron is entirely absent.

In the determination of water lost at 110 degrees from the unfused sediment the weighing had to be carried out with despatch. The powder is hygroscopic and regains a large proportion of this water on the balance pan.

³ Treadwell and Hall: *Analytical Chemistry*, vol. ii, 5th ed., 1919, p. 611.

TABLE I.—*Chemical Analyses of Core from Montezuma Well*

	1	2	3	4	5	6		7	8		9
						Differences			Percentage differences		
	Unfused	Fused	Fused	Unfused	Fused	+	—		+	—	
SiO ₂	61.72	64.17	64.40	61.76	61.76	....	....	....	....	....	
Al ₂ O ₃	17.05	17.12	17.18	17.07	16.48	....	0.59	....	....	(4)	
Fe ₂ O ₃	1.48	none	none	1.48	none	....	1.48	....	....	100	
FeO	2.64	6.50	6.53	2.64	6.26	3.62	....	137	....	....	
Fe .....	....	0.46	....	....	....	....	....	....	....	....	
MgO	1.54	1.52	1.52	1.54	1.46	....	0.08	....	....	(5)	
CaO	3.00	3.36	3.38	3.00	3.24	0.24	....	(8)	....	....	
Na ₂ O	3.28	3.41	3.42	3.28	3.28	....	....	....	....	....	
K ₂ O	2.09	2.21	2.22	2.09	2.13	0.04	....	(2)	....	....	
H ₂ O+	2.00	0.24	0.24	2.00	0.23	....	1.77	....	....	88	
H ₂ O—	3.47	0.02	0.02	3.48	0.02	....	3.46	....	....	99	
CO ₂	0.65	none	none	0.65	none	....	0.65	....	....	100	
TiO ₂	0.58	0.62	0.62	0.58	0.59	0.01	....	(2)	....	....	
P ₂ O ₅	0.21	0.28	0.28	0.21	0.27	0.06	....	(30)	....	....	
S	0.14	0.06	0.06	0.14	0.06	....	0.08	....	....	57	
Cr ₂ O ₃	trace	trace	trace	trace	trace	....	....	....	....	....	
MnO	0.06	0.07	0.07	0.06	0.07	0.01	....	(17)	....	....	
BaO	0.07	0.08	0.08	0.07	0.07	....	....	....	....	....	
Sum	99.98	100.12	100.02	100.05	95.92	3.98	8.11				
Less O.....	.05	.02	.02	.05	.02	....	.03				
Sum	99.93	100.10	100.00	100.00	95.90	....	8.08				
				95.90			3.98				
Percentage change on fusion.....				—4.10	....	....	—4.10				

1. Unfused Eocene (Tejon) sediment from core taken in Montezuma well, near Suisun, Solano County, California. M. Auroousseau, analyst.

2. Fused portion of core. M. Auroousseau, analyst.

3. Fused portion of core from (2) by deducting metallic iron and reducing to 100.

4. (1) calculated to 100.

5. Amount of each oxide associated with 61.76 grams of SiO₂ in fused material calculated from (3).

6. Positive differences.

7. Negative differences.

8. Positive percentage differences from amounts in original sediment.

9. Negative percentage differences from amounts in original sediment.

CHEMICAL EFFECTS OF FUSION

The analyses of the fused and unfused portions show very remarkable correspondence. There can be no doubt of the identity of the fused plug with the unfused sediment immediately overlying it, nor can there be

any doubt that the samples were representative to an unexpected degree. Our results, therefore, furnish a very trustworthy basis for a discussion of the chemical effects of fusion.

In order to compare the analyses, we have reduced them to a common silica basis by recalculating the analysis of the fused portion. Columns 4 and 5, Table I, therefore state the amounts of each oxide associated with 61.76 grams SiO_2 in both fused and unfused. Columns 6 and 7 show differences and columns 8 and 9 express these as percentages of the amounts present in the original unfused sediment. In these last two columns figures in brackets represent original differences between the fused and unfused material. For constituents present in accurately determinable amounts the differences range from 2 per cent to 8 per cent. Figures not in brackets represent the effects of fusion, and range from 57 per cent to 137 per cent. The differences in K_2O , TiO_2 , P_2O_5 , MnO , and possibly Al_2O_3 are within the limits of analytical error. Those in MgO , CaO , and perhaps Al_2O_3 represent actual differences between the two samples. A calculation from these two columns shows that the iron pipe has contributed 1.78 grams of iron (or 2.29 grams stated as FeO) to 100 grams of the original material, on fusion. In the oxidation of this additional iron to FeO and in the concomitant reduction of the original amount of Fe_2O_3 to FeO , there has been a change in oxygen content of +0.35 gram. This oxygen may be assumed to have come from the decomposition of water by metallic iron at the elevated temperature.

All the CO_2 , practically all the water, and about one-half of the sulphur have been driven off during the fusion. Only 0.26 per cent of water has actually remained in the fused product—a fact to which reference will be made later. The remaining percentage differences are to be attributed to actual variation, in reality very slight, in the nature of the material in the sedimentary column penetrated.

TEMPERATURE OF FUSION

We have made tests on the material of the core to determine the temperature required for fusion. When heated in air the rock powder is changed to a brick-red frit in which the iron has evidently been largely oxidized to the ferric state, and tests carried out under these conditions would give little indication of the temperature of fusion under the conditions of drilling. The tests were therefore made in a current of CO_2 and steam after a method devised by E. S. Shepherd, of this Laboratory, who has found that in such an atmosphere the state of oxidation of the

iron remains unchanged in silicate substances of moderate iron content.

When the material was heated in this way and the product examined under the microscope, it was found that at 1,050 degrees centigrade only a slight sintering was obtained, at 1,100 degrees centigrade a considerable amount of glass was formed, and at 1,150 degrees centigrade a proportion of glass was formed in one hour about equivalent to that formed in the fused part of the core. A temperature nearly, if not quite, as high as the last (1,150 degrees centigrade) must have been attained in the drill-hole in order to produce the results actually found. It is true that the fusion of the core took place under a head of water sufficient to give a pressure of about 150 atmospheres, but that this was not adequate to bring about significant solution of water in the silicate melt is plainly indicated by the analysis of the fused core, which shows only 0.26 per cent water, an amount of the order of magnitude to be expected from laboratory experience of the effects of such moderate pressures. For such a minute amount of water one can, with little fear of significant error, calculate, from the ordinary law of freezing-point lowering, its effect on the fusion temperature, and it will be found that a lowering of 15 degrees to 20 degrees centigrade is to be expected. Such a small effect has no importance in the present connection; nor can it be successfully maintained that the amount of water now present in the fusion is no indication of the amount formerly present. The core was very rapidly cooled, immediately on cessation of drilling, to a temperature at which the glass was rigid and in such a condition that no volatile matter could escape from it. Indeed, this cooling took place under the same head of water as that under which the fusion occurred; so that there would be no tendency toward the escape of water from the melt. Only after cooling was the core slowly raised to the surface.

The conditions are the reverse of those experienced by a natural water-bearing lava, which, when poured out on the surface, maintains its high temperature for a long period, relatively speaking, but has the pressure exerted on it suddenly reduced—a combination decidedly favorable to the escape of volatile matter. There is no avoiding the conclusion that the small amount of water present in the fused core represents all of that component that it was able to retain at the temperature and pressure existent during fusion. A temperature very nearly equal to that required for dry fusion must therefore have obtained.

CHANGES EFFECTED IN THE STEEL OF THE CORE BARREL

This conclusion as to the high temperature that was attained is completely confirmed by a study of the changes that have taken place in the

steel. A cutting from the tip of the core barrel and, for comparison, a cutting taken 2 feet higher up were submitted to the Bureau of Standards with the request that the temperature to which the tip was subjected be determined as closely as possible. The report was accompanied by two micrographs showing the difference in structure. These are reproduced in figure 3. The conclusion reached is that "the structure at the tip indicates that the metal was heated above the upper critical range (900 degrees centigrade) and then cooled fairly rapidly (more rapidly

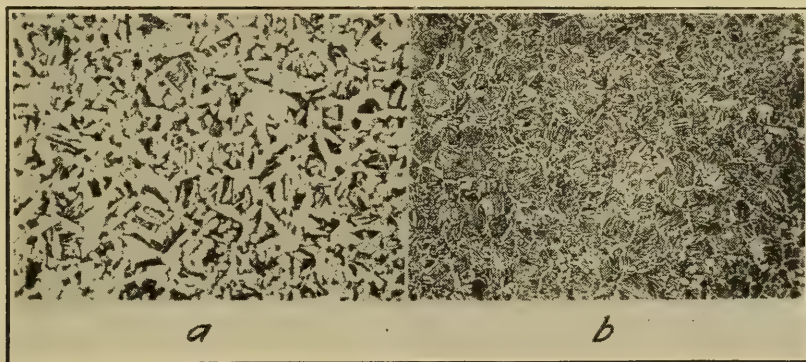


FIGURE 3.—*Micrographs of Steel from Core Barrel*

a, unheated steel 2 feet from tip; *b*, heated steel tip. The change of structure is due to the heating of the steel at tip to a temperature "as high as 1,050 degrees centigrade," followed by rapid cooling.

than in air). The tip of the pipe was not heated long enough to produce pronounced grain growth, which occurs in this type of steel after prolonged heating above 950 degrees centigrade. It was estimated, however, that the temperature reached was as high as 1,050 degrees centigrade."⁴ This independent evidence is in agreement with the conclusion reached on an earlier page, that the temperature was in the neighborhood of 1,100 degrees centigrade.

PRODUCTION OF HEAT BY FRICTION

It is rather difficult to picture the conditions under which a steel, heated to a temperature at which it can be forged, though not easily, could nevertheless act as an abrasive in cutting rock. It is to be noted, however, that on account of the good conductivity of the pipe only the extreme tip was so heated, so that a tearing off of the softened end would expose cooler and stronger steel for further cutting. As a matter of fact, it is very doubtful whether any further cutting was accomplished after this condition was reached. Probably the principal action at this

⁴ Report from Mr. S. Epstein: U. S. Bureau of Standards.

stage was a twisting of the rock contents of the core barrel on the rock immediately below it and of adjacent layers of the core material on each other. To such action rather than to the turning of steel on rock is to be assigned the larger measure of production of heat required for the fusion that resulted.

We may get an approximate figure for the heat produced by friction, since the pressure resting on the core and the rate of revolution are known with fair accuracy. The pressure was about 20 tons, the rate of revolution 25 per minute, the radius of gyration 1.5 inches, and the coefficient of friction of rock matter on rock may be as great as 1 or even greater.⁵ Taking a coefficient of friction of 1, it is found that about 3.14×10^7 foot-pounds of work would be expended in friction at or near the end of the core barrel in the 40 minutes during which very slow progress was made. This is equal to about 10^7 calories. Assuming a specific heat of 0.22 calorie for the material heated and a latent heat of 100 calories per gram, the amount of heat developed is sufficient to raise to 1,100 degrees and partially fuse (50 per cent conversion to liquid) about 37 kilos of rock. Only about 6 kilos of rock actually were so affected. Of course, all the heat generated would not be available for this effect. Some of it would be used in heating the surrounding rock, but this amount would probably not be great on account of the poor conductivity of rock, especially when porous. A large amount would be conducted away by the massive pipe line, but even this good conductor, with the tip heated to 1,100 degrees centigrade and a temperature of 100 degrees centigrade only 20 centimeters higher up the pipe, would carry away but 200 calories per second. The friction is capable of producing about 4,000 calories per second. It is not unreasonable to expect, then, that, of the heat produced, a sufficient quantity was available to melt 6 kilos of rock.

CORE FROM "MEYER 6" WELL OF THE UNION OIL COMPANY

This well is located at Santa Fe Springs, Los Angeles County, California. Professor Willis sent us part of the fused end of another core from the above-named locality, obtained at a depth of about 3,000 feet. No sample of the unfused sediment is available for comparison in this case; but, though much glass is formed, it is plain that the original was an arkose-like material of considerably coarser grain than the Montezuma sediment. The unfused grains are again quartz and plagioclase (about

⁵ Peele's Mining Engineers' Handbook, p. 1961.

Ab₂An₃) and there is a great abundance of small fragments of iron from the pipe.

The chemical composition of this core is shown in Table II. The amount of metallic iron was so high as to render useless Pratt's method for the determination of FeO. It was not found practicable to remove this iron with the electromagnet. The greater part of the error of analysis here undoubtedly devolves on the determination of metallic iron. Check determinations of the total iron were made and were in satisfactory agreement. From these the amount of FeO in the fusion was calculated by subtracting the metallic iron, expressed as FeO, from the total iron as FeO. Considerations similar to those given in connection with the Montezuma core lead us to believe that there is no ferric iron present.

TABLE II.—*Fused Core, "Meyer 6" Well, Santa Fe Springs, Los Angeles County, California*

	1	2	3	4
SiO ₂	65.45	65.11	68.95	68.16
Al ₂ O ₃	14.35	14.28	15.12	14.95
Fe ₂ O ₃	none	none	none	0.95
FeO	4.67	4.65	4.92	2.92
Fe	5.60	5.57	....	....
MgO	0.86	0.85	0.90	1.58
CaO	2.48	2.47	2.62	2.32
Na ₂ O	3.52	3.50	3.71	4.13
K ₂ O	2.90	2.88	3.06	2.89
H ₂ O+	0.13 }	0.18	0.19	{ 1.36
H ₂ O—	0.05 }			
CO ₂	none	none	none	....
TiO ₂	0.30	0.30	0.31	0.90
P ₂ O ₅	0.21	0.21	0.22	none
S	p. n. d.	p. n. d.	p. n. d.	....
FeS ₂ .....	....	....	....	0.03
MnO	p. n. d.	p. n. d.	p. n. d.	none
Sum	100.52	100.00	100.00	100.49

1. Composition of sample. M. Aurousseau, analyst.

2. The same, calculated to 100.

3. Composition of fused sedimentary material calculated from 1 by deducting metallic iron and reducing to 100.

4. Aplite, Zeia River, Amur District, Siberia. W. Giers, analyst. E. Ahnert, Expl. G. Reg. Aurif. Sib., X, Taf. VII, 1910.

The chemical analysis, recalculated by deducting metallic iron to determine the actual composition of the rock matter (Table II, number 3), confirms the indications of the microscope that the rock was of the nature

of arkose. It is rather closely paralleled in composition by an aplite from Siberia (Table II, number 4), but its norm (Table III, number 3) shows the same departure from typical igneous composition as do most sediments, though in this case it is of very moderate degree.

SYSTEMATIC POSITION OF THE FUSED SAMPLES

The analyses of the fused cores show that both differ in composition in the same way from ordinary characteristic sedimentary material (see Table III). The principal feldspar identifiable under the microscope in the original sediment of the Montezuma core is a basic plagioclase, but the analysis shows that the alkaline feldspars are much more abundant than the calcic. It can only be concluded that the finer-grained, so-called claylike, matter of the arkose and of the shaly layers in it is in reality but moderately kaolinized alkaline feldspars. Unquestionably the sediment is the result of processes in which rock comminution dominated over rock decay. The same would, no doubt, be true of the original sediment of the "Meyer 6" well as shown by the analysis of the core.

TABLE III.—*Normative Compositions and Systematic Positions of Cores*

	1	2	3
Quartz	22.64	25.26	25.20
Corundum	3.67	4.49	1.43
Orthoclase	12.79	12.79	18.35
Albite	28.82	29.34	31.44
Anorthite	15.29	15.29	11.68
Hypersthene	14.60	11.06	10.75
Ilmenite	1.22	1.37	0.61
Apatite	0.51	0.40	0.35
Pyrite	0.20	.....	.....
Water	0.26	.....	0.19
Sum	100.00	100.00	100.00
"II.4."3.4. (I)II.4.'3.4. I(II).4.2.(3)4.			
Tonalose. Tonalose. Lassenose.			

- 1. Fused core, Montezuma well, near Suisun, Solano County, California (number 3, Table I).
- 2. Hypothetical result of fusion of Montezuma sediment (number 3, Table IV).
- 3. Fused core, "Meyer 6" well, Santa Fe Springs, Los Angeles County, California, deducting metallic iron (number 3, Table II).

As a result of this fact, these cores depart but little in composition from an igneous rock. The Meyer core has already been compared with an aplitic rock. In Table IV the fused product from the Montezuma

well is compared with a malchite from Zwingenberg, Baden. It is possible also to match fairly closely the hypothetical fused product (calculated from the analysis of the original sediment assuming a loss of all volatile constituents and no addition of iron) with a quartz diorite from Electric Peak, Yellowstone National Park.

TABLE IV.—*Comparison of fused Core with igneous Rocks*

	1	2	3	4	5	6	7
SiO ₂	64.40	63.18	65.94	65.11	58.63	64.18	61.02
Al ₂ O ₃	17.18	17.03	18.21	16.21	18.59	16.91	15.85
Fe ₂ O ₃	none	0.24	none	1.06	1.93	4.44	3.92
FeO	6.53	6.37	4.24	3.19	6.46	3.05	3.48
MgO	1.52	0.92	1.65	2.57	2.62	3.07	3.60
CaO	3.38	4.17	3.26	3.97	0.56	3.41	5.24
Na ₂ O	3.42	4.44	3.50	4.00	2.58	1.39	3.96
K ₂ O	2.22	2.91	2.23	2.51	2.01	3.56	3.23
H ₂ O+	0.24	0.52	....	0.94	{ 4.45 1.38	....	....
H ₂ O—	0.02						
CO ₂	none	....	....	....	none	....	....
TiO ₂	0.62	....	0.62	0.71	1.01	....	....
P ₂ O ₅	0.28	0.23	0.22	0.02	0.08	....	....
SO ₃ .....	....	0.19	....	trace	....	....	....
Cl .....	....	....	....	none	....	....	....
S	0.06	....	....	....	none	....	....
Cr ₂ O ₃	trace	....	....	....	....	....	....
MnO	0.07	....	0.06	none	0.38	....	....
(NiCo)O .....	....	....	....	....	0.03	....	....
BaO	0.08	....	0.07	....	0.06	....	....
SrO .....	....	....	....	....	trace	....	....
Li ₂ O .....	....	....	....	0.04	....	....	....
Sum	100.02	100.20	100.00	100.33	100.77	100.00	100.00
Less O.....	.02	....	....	....	....	....	....
Sum	100.00	100.20	100.00	100.33	100.77	100.00	100.00

1. Fused core, Montezuma well (number 3, Table I).

2. Malchite, Zwingenberg, Melibocus Mountains, Baden. Heurich, analyst. A. Osann, Mitt. Bad. Geol. Land-Anst II, 1893, page 385.

3. Result of fusion of Tejon sediment of Montezuma well, assuming loss of volatile matter and no addition of iron.

4. Quartz diorite, Electric Peak, Yellowstone National Park. J. F. Whitfield, analyst. J. P. Iddings, United States Geological Survey, Annual Report XII, 1, 1891, page 627.

5. Buchite (fused phyllite) Sailean Sligenach, Ardmucknish, Argyllshire, Scotland. W. Pollard, analyst. Memoirs Geological Survey Scotland, number 45, 1908, page 132.

6. Average shale as calculated by Hobbs.

7. Average igneous rock as recalculated by Hobbs for principal constituents from the results of Clarke and Washington.

These rocks belong to the subrang tonalose, but inspection of this subrang in Washington's tables shows that they differ in composition from typical igneous rocks in the same way as the average shale differs from the average igneous rock. In the closest *general* matches obtainable, lime is distinctly higher and the ratio of soda to potash greater in the igneous rocks. Moreover, were all the analyses in columns 1-4 of Table IV reduced to 100 after excluding water, this divergence would be increased. It was also evident, in our endeavor to match an igneous rock with the Montezuma sediment, that the closer parallels were often igneous rocks of unusual compositions, such as schliers in granites. In matching the fused sediment from the Meyer well (see Table II) it was found that most of the lissenoses resembling it showed higher figures for $\text{MgO} + \text{CaO}$ and a greater ratio for soda over potash.

GENERAL CONSIDERATIONS REGARDING THE FUSIBILITY OF CORES

There is a very strong suggestion in the information gained from these and other studied cores that arkose is particularly susceptible to the fusing action here described. This is as it should be, for, contrary to the common misconception, a mixture rich in alkaline feldspars and quartz should constitute the most fusible material to be made up from ordinary rock-forming minerals. Frequently one will find in the literature the statement that femic material fuses more readily than salic; but this is due to the failure to distinguish between fusibility and fluidity. It is true that femic material forms a more fluid melt than salic material, but it is likewise true that a salic melt can be obtained at lower temperatures than can a femic melt. We refer here to anhydrous conditions, not to the conditions obtaining in magmas where this contrast is further emphasized by the fact that the salic magmas ordinarily contain more volatile matter than do the femic. The greater fusibility of salic material is well brought out in the studies of Sosman and Merwin on inclusions of arkose in the Palisade diabase, which were found to fuse in the laboratory at a temperature 100 degrees centigrade lower than the fusion temperature of the diabase.⁶

REFUSION OF SEDIMENTS AS A FACTOR IN MAGMA GENESIS

The arkosic nature of the sediment that was fused to form these cores and the consequent close chemical approach of the cores to an igneous rock are matters that require emphasis for another reason. Some geol-

⁶ Jour. Wash. Acad. Sci., vol. 3, 1913, p. 394.

ogists believe that igneous rocks are formed by the refusion of sediments, and the similarity of these cores to igneous rock might be regarded as furthering this belief. The original sediments were, however, in this case exceptional in character, and such material can not be regarded as generally available in large quantity for the desired action. Ordinary shales are, however, to be regarded as available in quantity, and Hobbs, one of the supporters of the refusion hypothesis, would make them the starting point for the formation of lavas.⁷

By tabulating side by side the chemical composition of average shale and of average igneous rocks (repeated here as columns 6 and 7 of Table IV), Hobbs is able to show a certain broad similarity. At the same time there are distinct differences that are thoroughly characteristic and carry with them definite consequences. The average shale shows a marked dominance of potash over soda and an excess of alumina over that required to make aluminosilicates with the alkalies and lime. Now, as a consequence of these characters, the refusion and recrystallization of such average shale would lead to the formation of such minerals as sillimanite and cordierite, which are not formed from uncontaminated igneous magmas. If igneous rocks are ordinarily the result of fusion of shale, the common absence of such minerals in them is rather surprising. Hobbs would supply the deficiency of alkaline and alkaline-earth bases in his fused shale by supposing that beds of limestone and of salt are absorbed by the melt as it rises toward the surface. Such absorption, though remarkably selective, can not be denied all credence, but one is still puzzled as to how this deficiency is made up in those laccoliths which he imagines to be the result of the fusion of shale *in situ*.

The chemical difficulties encountered by this hypothesis are, however, even less formidable than the thermal difficulties. Hobbs states that "most rocks would fuse at a depth of fifteen miles on the basis of dry conditions only." The temperature at this depth would be 740 degrees centigrade, accepting the geothermic gradient given by Hobbs, and even a salt bed would not melt at that temperature. For the dry fusion of the arkose of the Montezuma core a temperature corresponding to a depth of 23 miles would be required, and this arkose is certainly more fusible than typical shale. It is not, however, to dry fusion that Hobbs appeals for his principal results. Citing the known great effect of water in lowering the melting point of silicates, he imagines that the temperature at a depth of only 6 miles is adequate to melt shale. Again using

⁷ Earth evolution and its facial expression, New York, 1921, pp. 28-61; also Gerland's Beiträge zur Geophysik XII, 2, 1913, pp. 329-361.

the geothermic gradient given by Hobbs, we find this temperature to be about 315 degrees centigrade, which is scarcely acceptable as a temperature at which fusion of shale, even retaining its water, is to be credited. Particularly is this true when the nature of the process postulated is considered. The shale is supposed to fuse as a result of relief of pressure. Now, it is true that most silicates and silicate mixtures expand on melting, and that for any such mixture there is probably a combination of temperature and pressure conditions such that an isothermal⁸ relief of pressure would cause melting, though whether such a combination of temperature and pressure conditions obtains anywhere in the earth's crust is a question. But, even assuming that such a combination does obtain for anhydrous material, as soon as a volatile component enters into the system the whole aspect of affairs is changed. Thereafter the principal effect of lowering of pressure will be to decrease the amount of volatile component which the rock matter is capable of containing, with a consequent raising of the melting temperature. Plainly the great lowering of melting temperature through the presence (under pressure) of volatile matter, and the lowering of melting temperature by lowering of pressure in anhydrous silicates, can not be considered as working together in any hypothesis of magma genesis.

The only promising method of fusing shale would appear to be to have it exposed, retaining its water, to a temperature of some 850 degrees centigrade or more. If this temperature is to be the result of the normal thermal gradient, the requisite depth would presumably be about 17 miles. Under these conditions most shale would probably be fused, but, be it noted, relief of pressure would tend to cause it to crystallize. Whether shales ever become buried to such depths is questionable.

Under the influence of heat brought from the depths by basic magmas shales have sometimes been raised to some such temperature as that just mentioned and have been fused. An analysis of such fused shale (phylite) is given in Table IV, number 5. As will be noted, the conditions were such as to permit retention of water, which is probably essential to the fusion of shale by any magma. The process is probably one of no great quantitative importance, though possibly shale may, on occasion, be thus refused in sufficient amount to give rise by reintrusion to distinct bodies of small size. To such action may, perhaps, be attributed the abnormal volcanic necks in Lake Janisjarvi, Finland, described by Eskola.⁹

⁸ The word isothermal should be carefully noted. It is doubtful whether any such action could be realized in the earth's crust.

⁹ Bull. Com. Géol. Finlande, no. 55, 1921

SUMMARY

When a core sample of the beds penetrated is taken during the drilling of an oil well, it is found, under some conditions, that part of the core consists of a slaglike mass bearing some resemblance to a natural lava. This slag has been pronounced by some geologists to be the result of fusion of rock in the drill-hole as a result of the heat of friction, though some operators have been unwilling to accept this conclusion. The examination of two drill cores sent us by Prof. Bailey Willis, in one of which the beds immediately above the slag were well preserved, has confirmed the opinion that the slag is the result of fusion of the sedimentary rock in place. Chemical analyses of sediment and slag show that they are practically identical in composition, except that the fused part or slag has lost nearly all its water, all its CO_2 , and about one-half its sulphur, and has received a considerable contribution of iron from the drill pipe.

Thermal tests in the laboratory show that a temperature nearly, if not quite, as high as 1,150 degrees centigrade is necessary to produce the results actually obtained in drilling. A metallographic study of the steel shows that the temperature attained was 1,050 degrees centigrade or higher.

The chemical composition and the microscopic characters of the material fused show that it was of the nature of an arkose, a variety of sedimentary rock which appears to be particularly susceptible to such fusion. Since the rock was an arkose, the slag shows only a moderate departure in composition from an igneous rock, but the difference is none the less real and is in the same direction as that exhibited by typical shales. On account of the arkosic nature of the sediment the general chemical similarity of the slag and igneous material can not be regarded as affording any support to the theory that igneous rocks are formed by the fusion of shale, nor do the thermal results favor the view that remelting of shale could occur at moderate depths in the earth's crust (say 6 to 10 miles) unless the normal temperatures prevailing at such depths are notably augmented by intrusion of igneous matter from greater depths.

DISCUSSION

Dr. SIDNEY POWERS: This paper is interesting from the viewpoint of petroleum geology. These cores are taken with the rotary system of drilling, and an ordinary piece of pipe is attached to a sawtooth edge which is all rotated with whatever mud happens to be in the hole. The

weight of drill, with speed of rotation, fuses the cores in case the rotation is rapid, and the end of the core (barrel) is very commonly fused, sometimes partially fused. The material which is fused has become so common that we now call it *corite*. It was first found on the coast in drilling on salt domes. It is very common to use rotary drilling in fusing.

An article on core drilling appears in the Monthly Review of Oil Fields of California, published by the State of California.

CARNIVOROUS SAURISCHIA IN EUROPE SINCE THE
TRIASSIC ¹

BY F. VON HUENE

(Presented before the Paleontological Society December 30, 1922)

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INTRODUCTION

In the Jurassic and Cretaceous of England, and France particularly, but also in several other countries, many skeletons, and principally fragments of such, have been found, only a few of which have hitherto been described and named. Many of these remains have been referred to in the literature as *Megalosaurus bucklandi*. At present without special studies it is scarcely possible to ascertain what is meant by this term. Therefore I think it may be desirable to publish my studies on all of these forms, made in recent years in many museums of England, France and other parts of Europe, and in America, together with what is known from the literature.

Two years ago in another place ("Williston Memorial Volume," not yet published) I assembled and enumerated all these specimens. I found ninety-seven in Europe and fifteen in other parts of the world except North America, but not all of them were useful for accurate determination and comparison. The type specimens I have redescribed from my own observation and I have figured some and made restorations of a few of them. Several new species and even new genera have also been described.

¹ Manuscript received by the Secretary of the Society March 15, 1923.

SPECIMENS FROM LOWER LIAS AND LOWER OOLITE OF ENGLAND

In the English Lower Lias and in the Lower Oolite there are forms which, while closely related to the genus *Megalosaurus*, yet do not really belong to it, since they lie somewhere between *Teratosaurus* and *Megalosaurus*. For the present I shall not assign a name to this genus. The tibia of these specimens is characterized by a rudimentary crista lateralis at the lateral side of the proximal end and below its head. In *Teratosaurus* this crest is still missing and in *Megalosaurus* it is strongly developed. The species from the Parker collection (Oxford) from Nethercomb (*Humphriesi* horizon of the Lower Oolite) I have named "*Megalosaurus*" *nethercombensis* n. sp. Its pubis is rodlike in the distal (anterior) portion. The teeth are similar to those of the true *Megalosaurus bucklandi*, but, among other differences, are somewhat thicker than in that species.

The true *Megalosaurus bucklandi* occurs only in the Stonesfield slate just below the Great Oolitic. So much of the skull is preserved that a restoration, within certain limits of error, is possible. This skull exhibits some resemblance to *Antrodemus*. The cervical vertebræ are high, relatively short, and opisthocœlous. Neither the cervical nor the dorsal vertebræ show the pleurocentral excavations so sharply circumscribed or so deep as in *Streptospondylus* or in *Antrodemus*. The number of presacral vertebræ is not known, but there is no valid reason why it should differ from that in *Streptospondylus cuvieri*, which has nine cervical and fourteen dorsal vertebræ. The dorsal vertebræ show only pleurocentral depressions, but not cavities. Below the diapophysis are strong supporting buttresses, with deep niches between them. The neural process is broad and thick, but not very high. The sacrum, as is well known, consists of five vertebræ. The anterior caudal vertebræ are as long as the dorsals. The hæmapophyses are like those in *Antrodemus*. The scapula is long, slender, and straight, as in *Antrodemus*, and its processus deltoideus is very high. The humerus, which is robust, is about half the length of the femur and a little more than half the length of the scapula. The ulna and radius are scarcely more than half as long as the humerus and are extraordinarily stout. Unfortunately the manus is not known. In the pelvis the pubis is a narrow and distally rodlike bone, but is not completely known. The proximal expansion containing the obturator foramen disappears within a short distance of the proximal end. The ischium exhibits an angle in the middle of the shaft. The ilium is rather large and has a broad anterior spine. The trochanter major on the femur is a broad fanlike crest for the ilio femoral muscle, corresponding there-

fore with the large spina iliaca anterior. The distal condyles of the femur are separated by a broad groove even on the dorsal side. The tibia has a typical lateral crest near its proximal extremity. In the metatarsus a fifth metatarsal is not known and probably did not exist, so the pes stands between *Teratosaurus* and *Antrodemus*.

Deslongchamps's *Poikilopleuron bucklandi*, from the Middle Dogger of Normandy, is only a rather large *Megalosaurus*, probably of the same group as *M. bucklandi* at Stonesfield. Since the specific name of these certainly different species would now be the same, the latter might better be called *Megalosaurus poikilopleuron*. The bone which I had mistaken some time ago for a pubis is rather a scapula. As a pubis its dimensions should be double. Therefore my former conclusions made from the form of the "pubis" are invalid. Of considerable interest is the fore limb with the manus. The humerus is very stout. Its length I should estimate, from a special study, as about half of the length of the tibia. The forearm is extraordinarily short and heavy. The radius shows a prominent muscular process in the middle of its length. The manus has five fingers, as in the Triassic Plateosauridæ, and differs from the later Carnosauria. The manus is relatively large.

A very well known form from the Oxford clay is *Megalosaurus* (*Streptospondylus*) *cuvieri*, found in England and in Normandy. The best skeleton existing is that from Wolvercot in the Parker collection (Oxford), which I have studied in detail from Nopsca's short descriptions. The skull, much of which is rather complete, differs in some minor points from that of *Megalosaurus bucklandi*, of which much less is known. The importance of this specimen lies in the completeness of the vertebral series (nine cervicals, fourteen dorsals, the first three sacrals, and twenty-nine caudals). The cervical and anterior dorsal vertebræ are deeply opisthocœlous, but this condition decreases posteriorly. Especially well developed are the neatly circumscribed pleurocœlous cavities, also decreasing toward the tail, but in the anterior dorsals they are still quite distinct, although soon becoming flattened. The cervicals are relatively short and high and the dorsals are relatively low. The sacral vertebræ have saddle-shaped articular faces. The shoulder girdle is similar to that of *Megalosaurus bucklandi*. The humerus is less heavily built than in the latter form and has not half the length of the femur, or even of the tibia. The manus is relatively slender, but is incompletely known. In the pelvis the ilium is much like that of *Megalosaurus bucklandi* and the same is true of the pubis, which has the medial lamella more developed in the proximal portion. The distal extremity

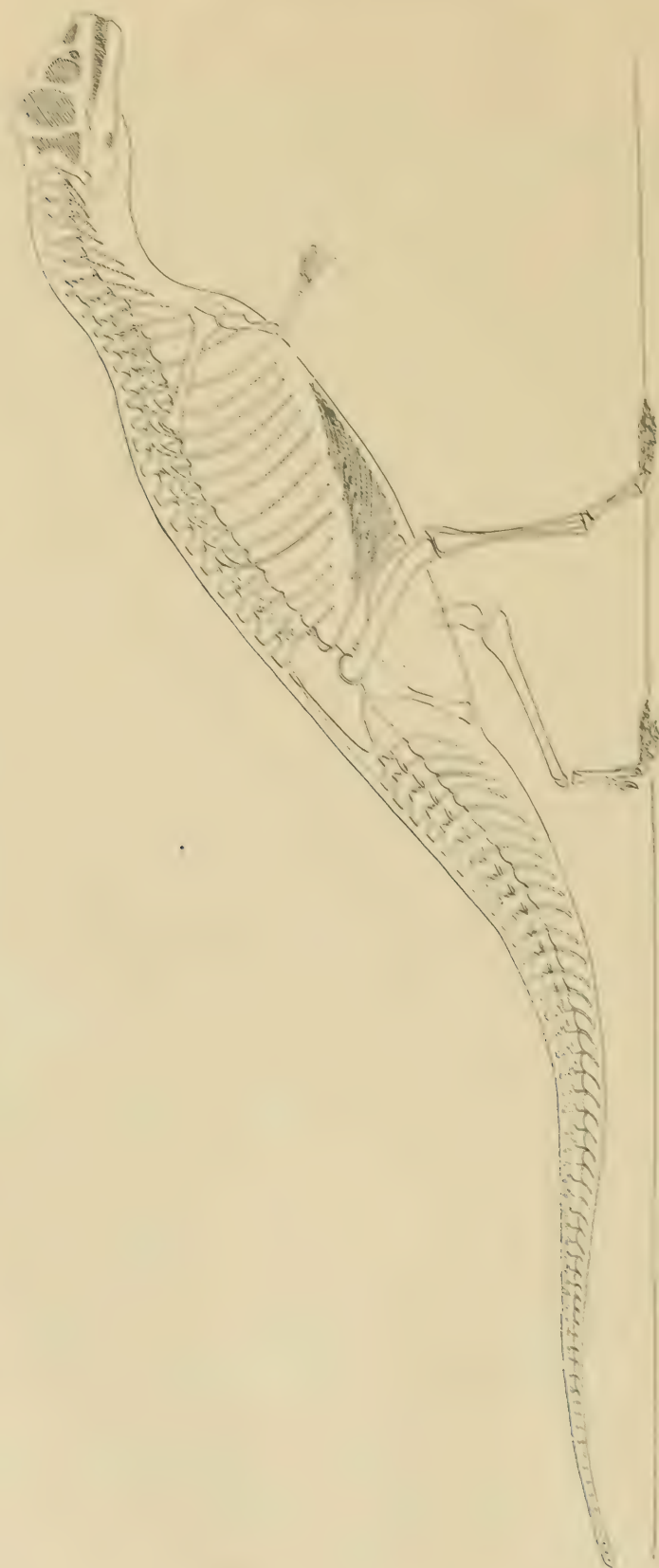


FIGURE 1.—New Restoration of *Megalosaurus (Streptospondylus) cuneirostris*

The restoration was made from Mr. Parker's specimen. Oxford clay, Wolvercot, Dorsetshire. Corrected in a few points from the Paris specimen from Honfleur. The missing parts are dotted. One-sixtieth natural size.

does not exhibit any hooklike thickening. The ischium differs from that of *Megalosaurus bucklandi* in having a rather straight shaft. The femur is less curved and the distal end is broader than in *Megalosaurus bucklandi*. The tibia has a well developed crista lateralis near its proximal extremity. The fibula is very slender. The form of the processus ascendens astragali resembles that of *Megalosaurus poikilopleuron*. The metatarsals and phalanges are much more slender than those of *M. bucklandi*. Although it is possible that a fifth toe once existed, there is now no indication of it. It is doubtful whether it is necessary to distinguish this species from the true *Megalosaurus* by a separate name (*Streptospondylus*). The reasons for doing so would be the deeper pleurocervical cavities and the slenderness and certain minor characters of the skull.

Another *Megalosaurus* from the Oxford clay of Weymouth (Dorsetshire) in the Parker collection I call *M. parkeri*. This specimen is characterized by high dorsal spines, an ilium differing in form from that of *M. bucklandi*, a very narrow pubis with large obturator foramen and a thick, hooked distal end, an ischium with lateral longitudinal ridge near the articular face, and a tibia whose cnemial crest projects greatly forward. This species differs more from the true *Megalosaurus* than does *M. curvieri*, only in another direction.

SPECIMEN FROM FRANCE

Of "*Megalosaurus*" *insignis* (De Longchamps), from the Kimmeridge of France, not much is known except large *Megalosaurus*-like teeth and stout phalanges.

The species described as *M. dunkeri* by Lydekker (Dames), from the English (and German) Lower Wealden, is distinguished from *Megalosaurus* by its enormously high neural spines in the dorsal region. I therefore propose to establish a new genus, *Altispinax*, for it. *M. oweni* (Lydekker), from the British Upper Wealden, belongs to the same genus. This genus apparently develops from *Megalosaurus parkeri*.

It is shown, therefore, that the true genus *Megalosaurus* occurs only in the Middle and Upper Dogger and lowest Malm. The earlier and later forms, although differing somewhat, are allied with it.

Quite a different form is that described by Sauvage as *Megalosaurus superbus*, which I call *Erectopus* (n. gen.) *superbus*, from the Middle Cretaceous of northern France. The relationships of this genus are not yet evident. It is characterized by the peculiar form of the femur. The proximal end above the trochanter major is greatly curved medially and the fibular condyle at the distal end is considerably more developed than

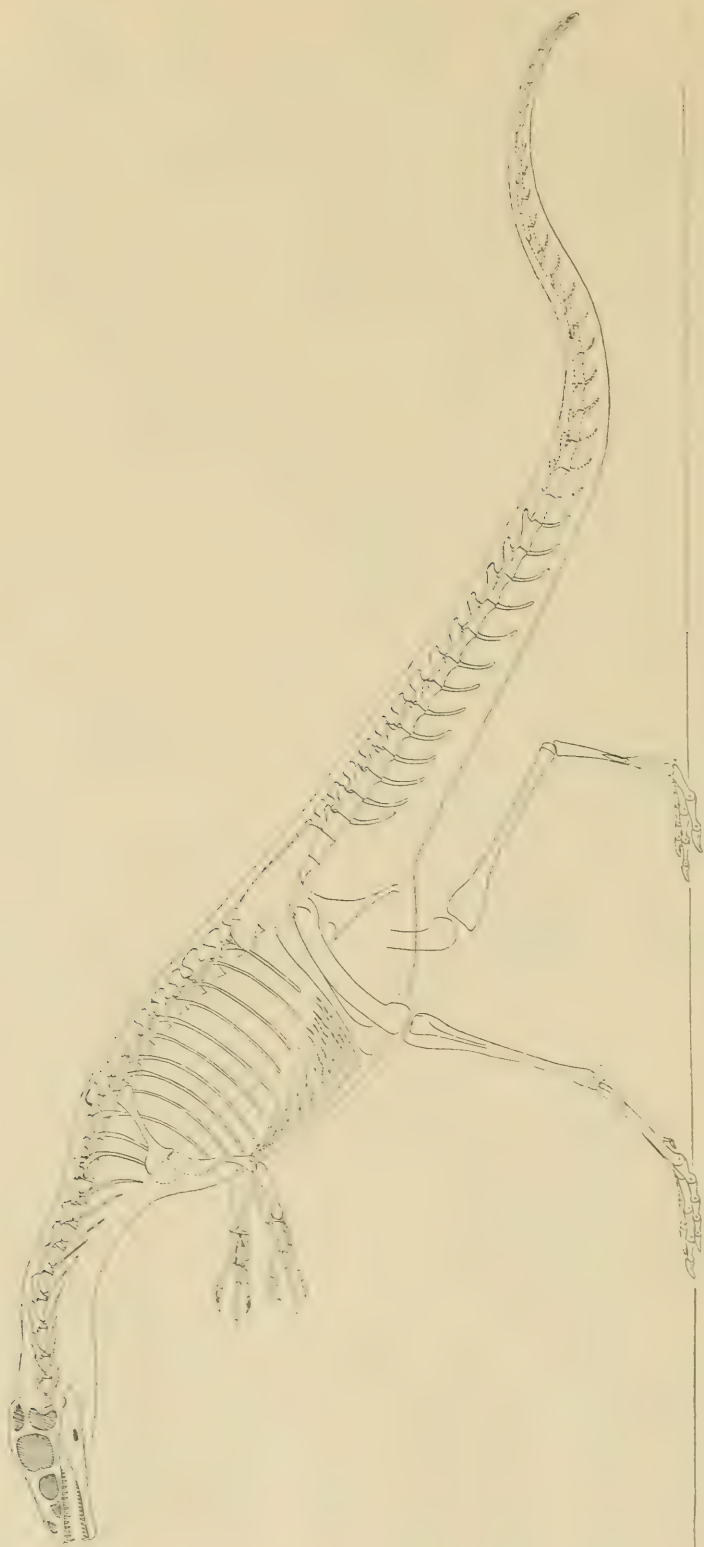


FIGURE 2.—*Ver* Restoration of *Compsognathus longipes*

This specimen is from the Portland of Solnhofen, Bavaria. The missing portions are dotted. One-twelfth natural size.

is the tibial condyle. This condition is the reverse of that found in the Megalosauridæ. The distal portion of the shaft is less curved than is the proximal half. From the curvature it is concluded that the whole hind limb was much straighter than in the Megalosauridæ. This is shown also by the position of the articular face of the caput femoris. The dorsal centra are relatively high. The tibia has a greatly projecting cnemial crest and the crista lateralis is unusually close to the proximal end of the bone. Metatarsal II is nearly half the length of the femur, which is exceptionally long. A portion of the manus is preserved, showing very slender phalanges. The first phalange of the thumb is short and the claws are small. An element found isolated is much like metacarpal V of the Plateosauridæ and of *Megalosaurus poikilopleuron*; it would be surprising, however, if a fifth digit were still present. All of these remains (and more) have been found so closely associated that they probably belong to a single individual.

All of the former genera belong to the Carnosauria. Of the Cœlurosauria there are but few forms. Of this group *Sarcosaurus woodi*, from the English Lower Lias, was recently described by Andrews. Ilium, pubis, and vertebræ exhibit the characteristic form, which is also seen in *Procompsognathus*, *Ornitholestes*, and *Ornithomimus*.

Compsognathus longipes (Wagner), from the Portland of Solenhofen, is well known. I have made a new restoration of the skull and of the whole skeleton. There are ten cervical vertebræ (beginning with the atlas), thirteen dorsals, and five sacrals. The humerus, although not distinctly recognizable at its proximal extremity, shows the processus lateralis extending two-thirds of the whole length of the bone. The reconstruction of the manus exhibits a form reminiscent of *Ornitholestes* and also of *Ornithomimus* in some respects. The skull, as in all Cœlurosauria, is much more primitive than in the Megalosauridæ, as is seen from the base of the skull, the palate, the temporal openings, and the large orbits.

The vertebra from the English Wealden *Calamospondylus foxi*, by Lydekker, is a cœlurid, and the sacral remains from the same horizon, which Seeley described as *Thecospondylus daviesi*, seem to me rather different from the other species of that (so-called) genus. I therefore propose the new generic name *Thecocœlurus*.

More satisfactory are the remains of *Aristosuchus pusillus* (Seeley), also from the Wealden of the Isle of Wight. The vertebræ, pubis, and claw show this specimen to be a true cœlurosaurian.

The claw described by Dollo as *Megalosaurus lonzeensis*, from the

Senonian of Namur, and the femur described by Seeley as *Megalosaurus bredai*, from the Maestricht beds, I consider ornithomimids.

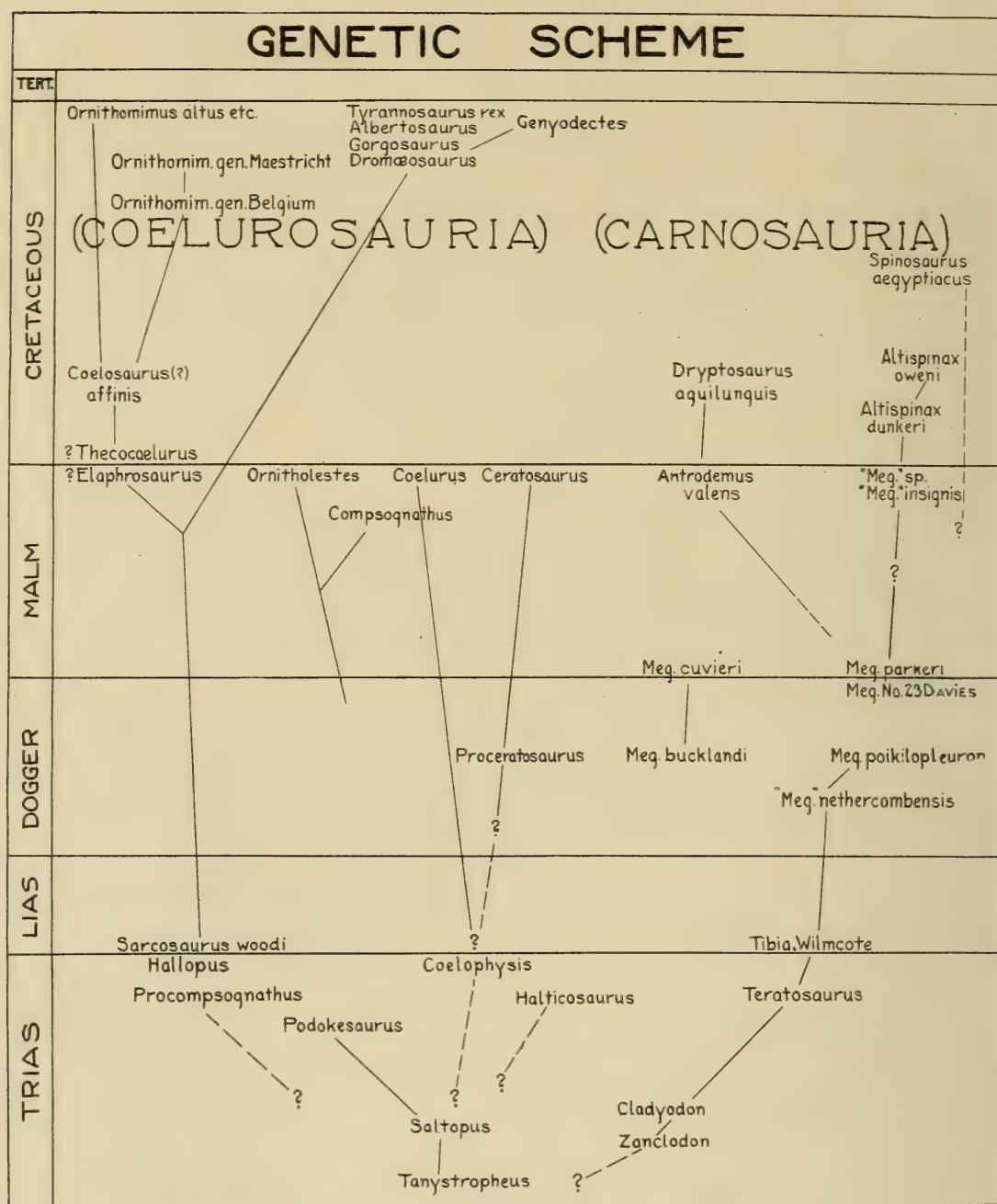


FIGURE 3.—Genetic Scheme

Among the extraeuropean skeletons Janenesch's *Elaphrosaurus bambergi*, from the Tendaguru Kimmeridgian, also belongs to the Cœlurosauria.

The American Morrison genus *Ceratosaurus* has also been recognized (the evidence is given elsewhere) as a cœlurosaurian, but resembling in some respects the Megalosauridæ.

HABITS OF THE MEGALOSAURIDÆ

I have discussed at length the phylogenetic and biological features in the paper mentioned above. For the former I give only a diagram and for the latter the following results:

The small fore limb of the Megalosauridæ, especially of the latest forms, and of the Deinodontidæ, with the large manus and enormous claws, which was no longer able to reach the mouth, could not have functioned in holding the prey or in tearing it to pieces. The hind limb, together with the mouth, must have been used for this purpose. The fore limb was doubtless useful in the killing of victims, in rivalry fights, in sexual activity, and in hatching and brooding the eggs and young. The relatively large fore limb of most of the Cœlurosauria, with its manus highly specialized on a primitive base, certainly served as a well developed grasping organ. It is supposed that the habits of *Ornithomimus* (*Struthiomimus*), the toothless terminal member of the Cœlurosauria, were adapted to digging out small vertebrates and other animals, or rather to scraping out and stealing the eggs of large reptiles which were hidden in the ground.

The opisthocœlous condition of the anterior presacral vertebræ of the Megalosauridæ and of the Deinodontidæ is explained as an adaptation to the habit of tearing the prey to pieces. The victim was probably held with the hind foot of the captor, the flesh was seized with its teeth and pulled off, upward and foreward, and in so doing the vertebral column had to double up and vigorously jerk upward.

In the cœlurosaurian genus *Ceratosaurus* a "quasi-opisthocœlous" condition is developed in the anterior presacral column, because it had adopted rapacious habits resembling those of the Megalosauridæ.

CONTRIBUTION TO THE VOMER-PARASPHENOID
QUESTION ¹

BY F. VON HUENE

(Presented before the Paleontological Society December 30, 1922)

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INTRODUCTION

Recently I have examined a very perfect skull of *Dicynodon sollasi* (Broom), of the Upper Permian *Endothiodon* beds from Biesjespoort, Cape Colony, South Africa,² which I had received as a kind donation from Dr. R. Broom. One of the results which seems to me of importance concerns the vomer question.

CHARACTER OF VENTRAL SIDE OF SKULL

The ventral side of this skull indicates the following characters:

The anterior portion of the basisphenoid possesses a long rostrum directed obliquely upward and in a higher plane than any part of the palate. The upper and posterior portion of it forms a thin and moderately high median blade, which I take for the presphenoid. The thicker and lower part of it, which extends to the anterior side of the orbits, I regard as the parasphenoid.

Below the branching of the rostrum basisphenoidei the pterygoid touches the basis cranii in the usual manner for a short distance undivided. It then separates anteriorly and thus forms a long and narrow interpterygoidal space. The latter is surrounded posteriorly by the

¹ Manuscript received by the Secretary of the Society March 15, 1923.

² Pal. Zeitschr., v, 1, 1922, pp. 58-71.

pterygoids and in the middle and anterior portion by the bones which I regard as the vomers. The pterygoid and the vomer are in contact. Between the greater portion of the vomer and the anterior extremity of the pterygoid the palatines are interlocked.

The internal nares are separated by a septum partly formed by the vomers (posteriorly and above) and partly by the fused premaxillæ, covering that part of the vomer from below. The lateral walls of the internal nares are formed by the palatines. Between the pterygoid, palatine, maxilla, and jugal the transversum is situated.

PRESENTATION OF THE IMPORTANT FACTS

These are the important facts.

The bones which I regard as the vomers are separated by the pterygoids from the basisphenoid by the length of the entire basis cranii, and

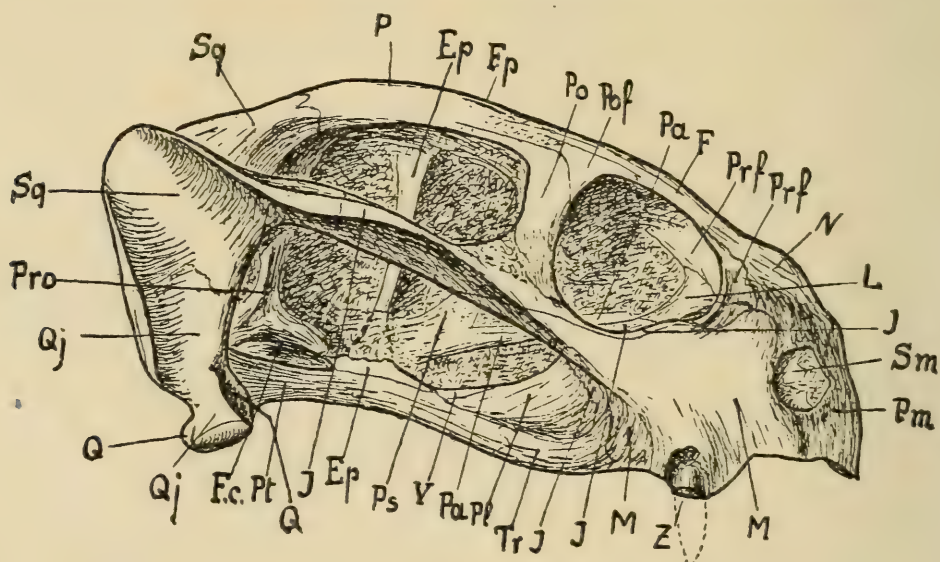


FIGURE 1.—*Dicynodon sollasi* Broom. Right side. Natural size.

are mainly situated just behind the internal nares. There is certainly a long interspace between the basisphenoid and the vomers and this space is occupied by the pterygoids. Therefore I can not adopt the interpretation of the paired vomers being in fact the parasphenoid. On the contrary, the true parasphenoid is present in the major portion of the rostrum basisphenoidei. It is useful also to compare the sections given by Sollas. It is quite true that the parasphenoid may extend for a considerable distance anteriorly and that the vomer may extend far posteriorly, but the main region of the parasphenoid is below and immediately in front of the basisphenoid, and the main region of the vomer

is in the neighborhood of the nasal capsule, originating on the ventral side of the paraseptal cartilage. The vomer in *Dicynodon* certainly appears to be a paired bone, and its relationships are like those in the mammals. The rostrum of the basis cranii I could not imagine as being the mammalian vomer.

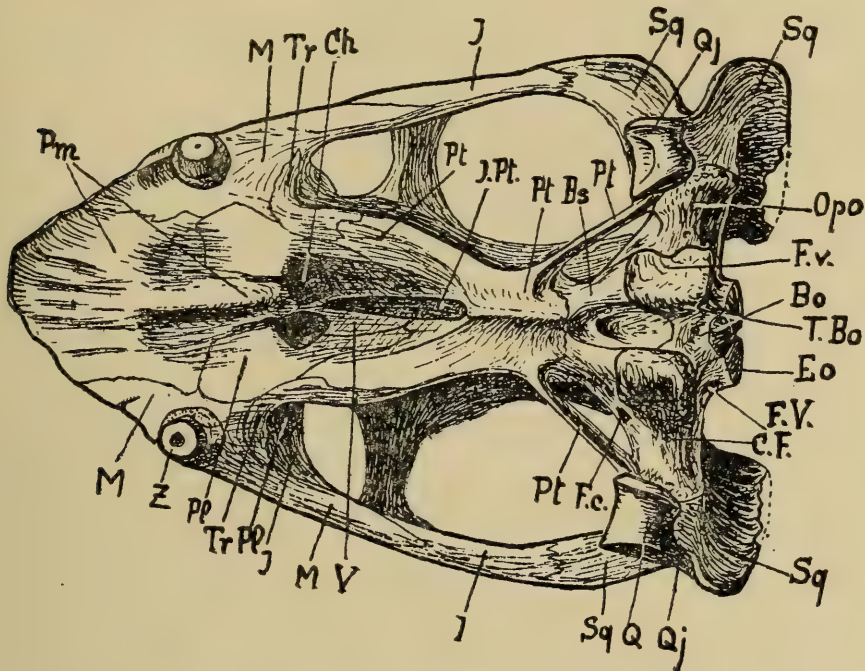


FIGURE 2.—*Dicynodon sollasi* Broom from below. Natural size.

- | | |
|----------------------------------|--------------------------------|
| Bo = Basioccipitale. | Pl = Palatinum. |
| Bs = Basisphenoid. | Pm = Præmaxilla. |
| Ch = Internal nares. | Po = Postorbitale. |
| Eo = Exoccipitale. | Pof = Postfrontale. |
| Ep = Epipterygoid. | Prf = Præfrontale. |
| F. c. = Foramen carotidis. | Pro = Prooticum. |
| F. p. = Foramen parietale. | Ps = Præspenoid. |
| F. v. = Fenestra vestibuli. | Pt = Pterygoid. |
| F. V. = Foramen vagi, etc. | Q = Quadratum. |
| J = Jugale. | Qj = Quadratojugale. |
| I. Pt. = Interpterygoidal space. | Sm = Septomaxillare. |
| L = Lacrymale. | Sq = Squamosum. |
| M = Maxilla. | T. Bo. = Tuber basioccipitale. |
| N = Nasale. | Tr. = Transversum. |
| Opo = Opisthoticum. | V = Vomer. |
| P = Parietale. | Z = Tooth. |
| Pa = Parasphenoid. | |

The distribution of the bones on the ventral side of the skull of *Dicynodon* (and also of all Theromorpha) does not differ greatly from that of the same region in the later reptiles, the Archosauria, as well as in the Stegocephalia and also in the mammals. Some of the earlier de-

scriptions of the theromorph palate seem to indicate quite a singular pattern, but I hope that after accurate investigation the arrangement and interpretation of this region in all theromorphs will turn out to be the same as in this *Dicynodon* skull, which quite agrees with the archosaurian type.

LINES OF PHYLETIC AND BIOLOGICAL DEVELOPMENT OF THE ICHTHYOPTERYGIA¹

BY F. VON HUENE

(Presented before the Paleontological Society December 30, 1922)

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INTRODUCTION

The great order of the Ichthyopterygia, known from Permian to Upper Cretaceous times, is formed by the Ichthyosauria, Omphalosauria, and Mesosauria.

A special study of all Liassic Ichthyosauria from the English and German Lias led me to a synoptic classification, which has also extended over all Jurassic and Cretaceous forms. Those of the Triassic are already well known from the classic memoirs of Merriam. Through recent additional observations of the extensive *Mesosaurus* material at Tübingen (from Brazil) this group may be reinterpreted and reviewed. Therefore it is possible for the first time to form an idea of this highly diversified and long-lived order of the Ichthyopterygia.²

MESOSAURIA

I need not repeat the reasons why the Mesosauria can not possibly be the forerunners of the Ichthyosauria,³ but many features in the skull and skeleton demonstrate convincingly their common origin. The Mesosauria

¹ Manuscript received by the Secretary of the Society March 15, 1923.

² F. von Huene: "Die Ichthyosaurier des Lias und ihre Zusammenhänge." Ed. by Gebrüder Borntraeger, Berlin, November, 1922, vii, 114 p., 22 pls. Quarto.

³ N. Jahrb. f. Min., etc., 1910, ii, pp. 29-69.

are, it appears to me, a primitive short side branch of the theoretic main line leading to the ichthyosaurs.

This primitive group, which has not yet been found in the Permian, but which certainly existed in that epoch, must have been a parallel branch with the Cotylosauria, both having sprung from the Carboniferous Embolomeri. The evidence for this is given in detail in the paper cited above.

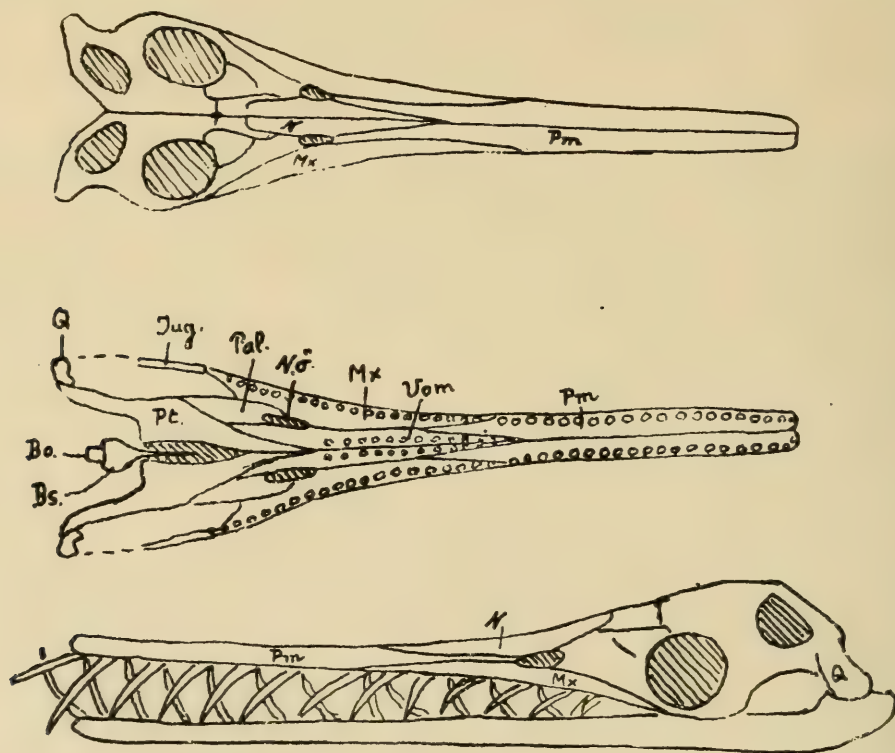


FIGURE 1.—New Restoration of the Skull of *Mesosaurus braziliensis* from the Permian of Irah, Brazil

Natural size. From specimens at the University of Tübingen.

Bo = Basioccipitale.
Bs = Basisphenoid.
Jug = Jugale.
Mx = Maxilla.
N = Nasale.
No = Internal nares.

Pal = Palatinum.
Pm = Præmaxilla.
Pt = Pterygoid.
Q = Quadratum.
Vom = Vomer.

OMPHALOSAURUS

Omphalosaurus is a coastal remnant of rather primitive Ichthyosauria, which have not yet become so well adapted to marine habits as have later forms. Both Mesosauria and Omphalosauria exhibit marked evidence of pachyostosis, according to Nopsca,⁴ and are therefore on the way toward aquatic adaptation.

⁴ Anatom. Anzeiger, 1922; Palæont. Zeitschr., v, 3, 1922. Both papers are still in press.

LATIPINNATIDÆ AND LONGIPINNATIDÆ

In the Triassic the Ichthyosauria already appear, divided into two main lines, the Latipinnatidæ and the Longipinnatidæ.

The first known latipinnatid is *Mixosaurus*, from the Muschelkalk. Its direct descendant in the Lower Lias of England is the genus *Eurypterygius* (Jaekel), with the well known species *E. communis*, *intermedius*, and others having ribs with divided heads and pelvis consisting of three separate bones. In the Upper Jurassic the latipinnatid group is represented by several new genera: (1) *Macropterygius* (= group of *I. trigonus*, with extremely large paddles, ribs as in *Ophthalmosaurus*, pelvis consisting of three separate bones, trunk long, tail short, teeth covered at the root with a mantle of cement), which is continued into the Middle and Upper Cretaceous (until Senonian); (2) *Myopterygius* (= *campylodon* group, in some respects similar to the former, but with enormous trochanters on the humerus and femur, and with differences in the skull); (3) the well known *Ophthalmosaurus* (incl. *Baptanodon*) (intermedium between radius and ulna, vertebral column and ribs similar to *Macropterygius*, pubis and ischium coalesced); (4) *Brachypterygius* (*extremus*, only radius and ulna in contact with the humerus, but with large sesamoid ossifications on both borders of the paddle, beginning at its proximal end).

The longipinnatid line, beginning with *Cymbospondylus* in the Middle Triassic, is still more highly varied than the latipinnatids, but more so in the early Mesozoic. In some respects *Cymbospondylus* is still more primitive than *Mixosaurus* in the proportions of the body, which has (as compared with *Ichthyosaurus*) an extraordinarily small head and very long and large paddles, especially the posterior pair. All the different shastasaurids have a short life and a rapid development. One line, which can not be included in the shastasaurids, but is related to this group, extends into and through the Lias. For this group I have proposed the generic name *Leptopterygius*. Some Rhætic forms, and the well known species *I. platyodon*, *lonchiodon*, *tenuirostris*, etcetera, of the Lower and *acutirostris* and *integer* of the Upper Lias, constitute this genus and are characterized by proximally undivided ribs (but nevertheless with two articulations) and by three separate bones in the pelvis. A special form of this group is *Eurhinosaurus* (Abel) *longirostris* in the Upper Lias. So the whole of this highly diversified main line of the Longipinnatidæ does not extend beyond the Liassic, and even in the Triassic has disappeared almost entirely.

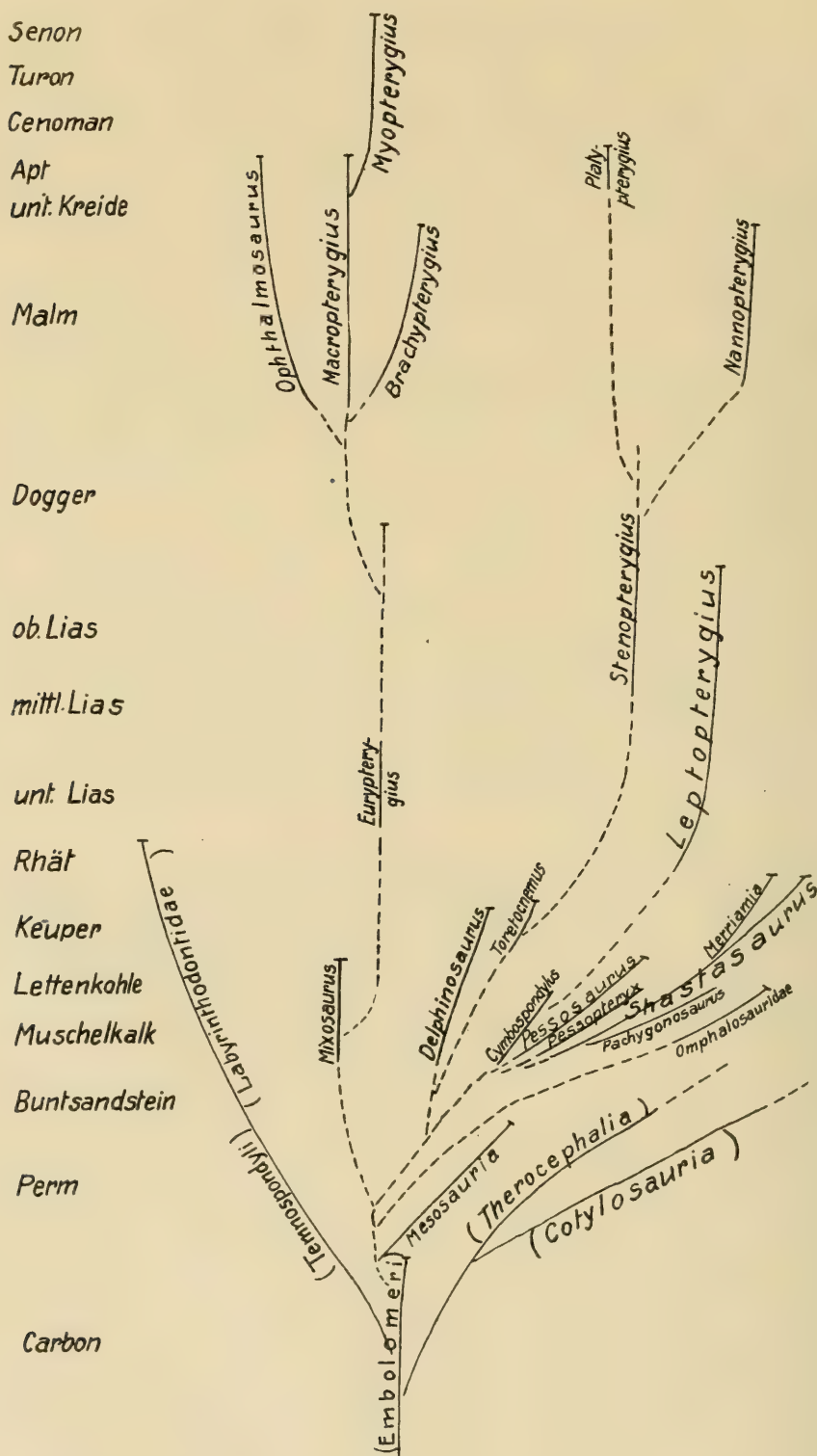


FIGURE 2.—Scheme of the phylogenetic Development of the Ichthyopterygia

There are, however, other longipinnatids which are still rare in the Triassic (I refer especially to *Toretocnemus*, with ribs much divided proximally), but which branch out in the Liassic and later form *Stenopterygius*, including *quadricissus* and many others. These animals are very perfectly adapted to a swimming mode of life, no less than are the contemporaneous latipinnatids. Throughout the Upper Jurassic forms are found with very small paddles and exceptionally strong tail (the functions of which compensate each other) of the group *Ichthyosaurus euthecodon*. I have proposed for them the new generic name *Nannopterygius*. There is a form in the Middle Cretaceous described by Broili as *I. platydactylus*, which has specialized in another direction. This form has very broad paddles, with sesamoid bones at the anterior and posterior borders. The tip of the tail was short and the animal was probably therefore a very poor propeller. This genus I call *Platypterygius*. It is the latest latipinnatid known.

Land tetrapods when first adopting aquatic life row with both pairs of extremities, a condition seen in the Mesosauria. The better adapted they become to that mode of locomotion, the more the function of the hind limbs is emphasized (as, for instance, in the crocodiles). This is still seen to some extent in one division of the Longipinnatidæ, namely, *Cymbospondylus*, the shastasaurids and *Leptopterygius*. Originally the slender, long-tailed bodies of the unknown earliest ichthyosaurs probably swam with a natural serpentine motion. By and by this was found useful for propulsion and became more localized in the flexible tail. In the same degree the neck was shortened and the head enlarged. This must have been true of all Ichthyosauria, but to a greater extent in the branch which later became the Latipinnatidæ. The function of the tail must very early have become one of propulsion, and at its strongest point a fin border ("Flossensaum") was acquired, later developing into a more or less symmetrical diplocercal caudal fin for a propeller. For a long time the paddles remained as organs of propulsion, and were used for that purpose in most of the earlier longipinnatids, but in the *Stenopterygius* branch and in all later longipinnatids, as well as in all latipinnatids, the hind paddles became reduced because of the perfect function of the tail-propeller and the fore paddles became more and more enlarged for vertical steering and for balancing. In the fore paddle of the latipinnatids the number of digits is not reduced, as it is in all longipinnatids. This may be explained by a differentiation in the very earliest mode of adaptation, when the two main divisions of the ichthyosaurs were just forming. In swimming, the upper wing of the diplocercal caudal

fin, being immobile, together with the dorsal fin, functions as a rudder. The wriggling lower wing of the caudal fin acts as a propeller. In the later Mesozoic ichthyosaurs the trunk becomes relatively longer and the anterior half of the tail is shortened. Therefore the whole body becomes more torpedo-like and better adapted for swimming, as in the modern *Xiphias gladius*.

IS THE CHANNEL OF THE MISSOURI RIVER THROUGH NORTH DAKOTA OF TERTIARY ORIGIN?¹

BY JAMES E. TODD

(Presented before the Society December 29, 1921)

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¹ Manuscript received by the Secretary of the Society June 16, 1922.

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INTRODUCTORY

For years it has been believed that the Missouri River owed its present course very largely to the influence of ice-sheets. This was first recognized by General G. K. Warren in 1868. In 1916 Prof. A. G. Leonard, State Geologist of North Dakota, published his conclusion, after some years of study, that the channel of the Missouri through North Dakota was of Tertiary origin, and that the ice-sheets of the Pleistocene had little effect upon its course.

This conclusion is diametrically opposed to that of South Dakota geologists; consequently the writer undertakes in this paper to show the errors of Dr. Leonard and, on the contrary, the reasons for believing that before the ice-sheet influenced the Missouri River the Missouri was made up of various streams leading to the north and east, and that the ice, by damming them, caused the water accumulating along its western edge to form a series of lakes and channels which eventually determined the present course of the Missouri of the Pleistocene in the Wisconsin stage.

ACKNOWLEDGMENTS

The material for this paper has mostly been gathered incidentally during several seasons' work, years ago, for the United States Geological Survey and for the South Dakota Geological Survey. More recently the Chicago, Milwaukee and Saint Paul Railway Company presented me with profiles of their lines west of the Missouri River in South Dakota, and the Minnesota and Saint Louis Railroad Company did likewise with their lines to Leola and Le Beau.

I am most grateful to Messrs. Norbeck and Nicholson, well-drillers, Redfield, South Dakota, for the free use of an auto and chauffeur for a week in Cheyenne River Indian Reservation.

The writer has not been personally familiar with facts concerning the Missouri above Bismarck and has depended almost entirely upon the reports of the North Dakota Geological Survey and a few articles in geological periodicals.

DR. LEONARD FOR THE AFFIRMATIVE

Dr. Leonard, in his paper before the Geological Society of America, gives his reasons so clearly and concisely we quote them in full. We

have inserted numbers to indicate the different arguments and also for reference.²

1. "The valley of Snake Creek is no larger than the valleys of other tributaries entering the Missouri above this point, and the notch in the east front

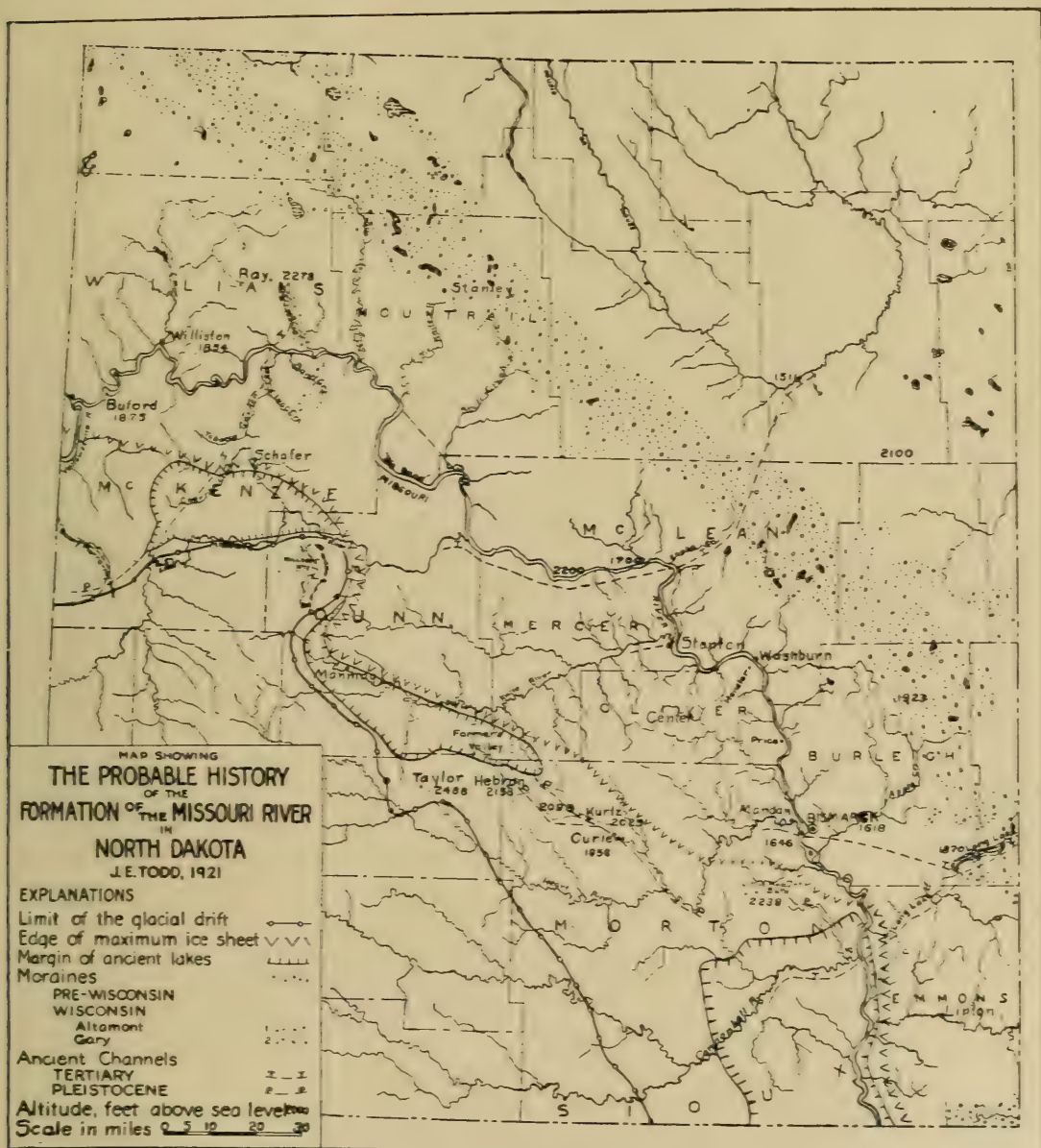


FIGURE 1.—Map of North Dakota

Showing probable history of the formation of the Missouri River in North Dakota.

of the divide north of Fort Stevenson, which is shown on some maps, does not exist in reality, and there is no evidence of any preglacial valley here. The valley of Long Lake Creek could hardly have been the eastward extension of the Cannon Ball River valley, since its lower course is not opposite

² Bull. Geol. Soc. Am., vol. 27, p. 295.

the mouth of the latter stream, but joins the Missouri four miles to the north. There is no reason for believing that the Knife River ever joined the Missouri near Fort Stevenson, and the lower valley of this stream has every appearance of great age, having a broad floodplain and gentle slopes. It is clearly a preglacial valley. The Heart River is thus the only important tributary of the Missouri which might have continued eastward to the James River if the valley of Apple Creek, which has its mouth just opposite the Heart, is an indication of this. But Apple Creek is readily accounted for as a preglacial tributary of the Missouri and one of the chief outlets for the glacial waters when the ice-margin occupied the position marked by the Altamont moraine. Its valley is largely filled with glacial outwash from the moraine."

2. "There is abundant evidence that the Missouri Valley below the mouth of Snake Creek is preglacial, and that the river was not forced by the ice-sheet to take its present southerly course through North Dakota. This evidence is based on the presence of glacial boulders on the valley bottom and at many points on a terrace representing a former floodplain of the Missouri. Boulders have been encountered in two wells in Bismarck at a depth of 125 feet below the surface or 80 feet below river level. These wells are near the edge of the terrace bordering the Missouri Valley at Bismarck, and since the boulders rest on the bedrock they indicate that the valley was excavated to this depth prior to the Glacial period. In several borings made for the Northern Pacific Railroad previous to the building of its bridge across the river at Bismarck, from 70 to 80 feet of silt and gravel were passed through before reaching the bedrock, and in one boring a boulder was struck at a depth of about 50 feet below the river bed."

3. "On the west side of the Missouri Valley, between Mandan and the mouth of the Knife River, there is a well developed terrace which in places is a mile and more wide. This terrace has an elevation of 55 to 60 above the river and the upper portion of it is in many places composed of glacial gravel and good-sized boulders. A railroad cut in this terrace a mile northeast of Mandan, near the cemetery, shows the following section:

	Feet.	Inches.*
Soil	2-3	
Boulders and gravel.....	5-9	
Sand, finely laminated, with several thin layers of gravel....	2-5	
Boulders and pebbles.....		6-12
Lance beds, exposed above railroad track.....	15	

"In another cut less than one-quarter of a mile south a bed of boulders, many of them several feet in diameter, mixed with gravel and resting on the Lance beds, extends a distance of at least 100 yards along the railroad.

"Several miles south of Price the upper part of the terrace is composed of boulders and coarse gravel, the deposit having a thickness of 5 to 6 feet."

4. "Between Sawyer and Price the terrace is finely developed and is covered in some places by a layer of gravel and boulders; in other places by unstratified glacial drift or boulder-clay. In the vicinity of Hensler the Missouri Valley is several miles wide, and here, as well as in other places, numbers of low, rounded drift hills, covered with numerous boulders, rest on

the valley floor. Some of the railroad cuts show the boulder-clay to be 30 to 40 feet thick.

"Before the time of the earlier ice-invasion, when the ice-sheet advanced 40 to 50 miles beyond the Missouri River, that stream must have flowed in its present broad, terraced valley, and on the floor of this valley the glacier deposited the boulders, gravel, and till so well exposed at many points. These deposits, shown in the railroad cuts of the terrace, lie about 40 feet above the ordinary stage of the river and vary considerably in thickness."

5. "Additional evidence that the present valley is preglacial, and that the trench of the river was excavated to its present depth at the time of the earlier ice-invasion, is shown by the boulder bed less than half a mile below the mouth of Tobacco Garden Creek. This bed of boulders, which lies just above the river level, is at least 12 to 14 feet thick and extends along the water's edge for a distance of 100 yards, while scattered boulders and ferruginous gravel occur at intervals for another 200 yards. Overlying the boulders are 15 feet of gravel.

"While some of the boulders of this deposit may have been brought here by floating ice, it is probable that most of the deposit was left here by the pre-Wisconsin ice-sheet when it advanced south of the river. The finer materials of the drift, if they were ever present, have been carried away, leaving the gravel and boulders."

Dr. Leonard has recently noted very many other exposures showing the relation of the drift to the earlier rocks.³

DISCUSSION OF ARGUMENTS

DR. LEONARD'S ARGUMENTS INADEQUATE

The arguments offered seem insufficient to establish the position taken by Dr. Leonard, for most of them are negative, not having a positive effect upon the problem.

NO TRACE OF OLD CHANNELS

1. The first point is that no trace has been found of any important channel leading north or east, and from the present knowledge of facts, viewed from his standpoint, he concludes the evidence is strongly in favor of his position. It should be remembered that there are few deep wells or drill-holes on the Coteau du Missouri. Judging from similar areas elsewhere, we may be very doubtful of this being a positive argument. Till or boulder-clay is frequently found 200 to 500 feet in thickness, as, for example, in northeastern South Dakota, on the Coteau des Prairies, or in central Iowa, on the divide northwest of Des Moines. For aught we know, there may be a buried valley 200 feet deep across the plateau east of the Missouri River into the Souris Valley or James River Valley.

³ Journal of Geology, vol. 24, no. 6.

There may be little trace of such a valley. The surface which was glaciated in the Wisconsin stage and the sheet of till left has been so little eroded that the lines of drainage, possibly resulting from the configuration of the preglacial surface, have not been distinctly outlined.

GLACIAL BOULDERS NEAR BISMARCK

2. The finding of boulders 125 feet below the surface at Bismarck is also inconclusive. It is known that in time of flood streams scour out their beds to an indefinite extent. This takes place especially in the narrow portion of the course. There the velocity of the stream is quickened and its eroding and transporting power are increased.⁴

The depths to which rivers may scour in this way has been found to be far beyond what most students heretofore have recognized. Surface conditions may be considered as deepening such erosion. Fine material, such as sand, may be picked up quickly, while heavy material may be very little affected; and yet, when we think of the rounded character of the pebbles within a short distance of their starting point, we may be assured that they also are moved in time of flood to an indefinite degree. It will be readily accepted that the coarser the material the less distance it is transported and the more promptly it will be dropped.

It is a question as to how deep such scouring may extend. It is very important in the Missouri River. It has been known by direct measurement that the bottom of the river, which may be only 15 feet in depth at ordinary stage, may be in a few hours deepened to 90 or even 100 feet at some places. In the valley of the Missouri River the depth of such influence seems to have been 125 to 150 feet below the surface of the bottom land. The depth, no doubt, increases with the volume of the stream and the softness of bedrock below. When we remember the shaly and clayey nature of bedrock at Bismarck and the tremendous floods poured out from the melting glacier of the Wisconsin stage, a depth of 125 feet is not therefore enough to be very sure.

A recent paper by Dr. E. B. Matthews discusses "The deeps of the lower Susquehanna river."⁵ It seems probable that those deeps are due to the erosive as well as solvent action of the water of the river and may be considered as formed analogous to the scour of streams, which we have been discussing. Some of those deeps were over 150 feet in depth. The full significance of the boulders at Bismarck is simply that they were deposited at a stage of the river when the 30-foot terrace was formed, which, from the configuration of the surface, seems to have been in the

⁴ Bulletin 158, U. S. Geol. Surv., p. 150.

⁵ Bull. Geol. Soc. Am., vol. 30.

later stages of the flood following the Wisconsin stage of the ice-sheet. At that time the Missouri was at a very high flood stage and sufficient to scour and fill to that depth. We can not conclude more than that the deposits were later than the beginning of the Glacial period.

GLACIAL GRAVELS IN TERRACES

3. He appeals to the occurrence of drift gravel deposits as affording evidence of preglacial origin of the valley in which they are found. Much that has been said in the last section may be applicable here. To show that the mere presence of stream deposits, including glacial boulders, does not prove the presence of ice in the close vicinity, much less at the identical locality, drift boulders and gravel may be found scores of miles from the edge of the ice which brought the boulders.

GLACIAL TILLS

4. The occurrence of typical till or boulder-clay at any point is considered good evidence that the ice has been at that point at a time beginning with the age of the bottom of the till; for it is generally conceded that till is on the immediate edge or presence of an ice-sheet. If Dr. Leonard can establish the existence of typical till on the terrace near Hensler, we are bound to believe that an ice-sheet reached that point and remained there long enough to deposit the depth of the till there found; but this may be true of the locality near Hensler without proving that the valley is the Missouri Valley. To one who suspects that the Missouri was formed as was outlined in previous section, the finding here of a valley deeper than usual may be plausibly ascribed to the valley of a river leading northeast, which from its greater age or more active drainage had excavated deeper than adjacent valleys. There is nothing improbable in the different valleys crossed by the course of the Missouri varying greatly in age and degree of erosion. Why may we not infer that preglacial Heart River turned north in the vicinity of Bismarek and drained independently, or with Knife River as a tributary, into the Souris River? Such conditions would favor more rapid erosion. Moreover, the material in which the basin of the Knife River is excavated is largely composed of soft beds of the Laramie.

BOULDER BAR NEAR MOUTH OF TOBACCO GARDEN CREEK

5. He argues that beds of boulders near the mouth of Tobacco Garden Creek indicate the preglacial formation of the valley in which they occur. But boulder bars, as they may be called, in river beds are formed not very uncommonly. They, of course, are evidence that they have been formed

since the Glacial period, but really they are no more significant of the preglacial age of the channel than are the boulders which are considered under head number 2. It seems probable that the accumulation of boulders mentioned has been formed some time since the Glacial period, and the later erosion of the stream has left it as a low terrace.

In the same region, river gravels containing glacial boulders are found at a much higher elevation at Glass Bluff,⁶ about 4 miles southeast of Buford. There "glacial drift" is found resting upon Laramie strata 200 feet above the river. Dr. Leonard reports three localities showing similar relations of drift to underlying rocks, one being a few miles below Glass Bluff and another at White Earth Creek north of the Missouri. Several other localities showing similar position by their altitude above the river are not given.⁶

Bauer reports several feet of drift gravel capping flat-topped buttes or fragments of a terrace along the lower course of the Little Missouri River.⁷ He thinks they may be of late Tertiary origin. These gravel beds are strong evidence that the plane of drainage has been for some time at that level since the beginning of the Glacial period. If the bed of the Missouri were as deep as Dr. Leonard believes, before the coming of the ice, what filled the valley of the stream to force the water so high above the bottom of the valley? If the glacier advanced, it might fill the valley with till, but we can scarcely believe that later erosion would carry it away. It would resist erosion more readily than the surrounding Laramie beds. We therefore consider that the existence of these gravel beds is a strong argument against the preglacial excavation of the valley.

EVIDENCE FROM SOUTH DAKOTA

GENERAL STATEMENT

According to Dr. Leonard's view, at the beginning of the Wisconsin stage the Missouri River was flowing at as low a level as, or even lower than, at the present time throughout its course in the State of North Dakota.

The State of South Dakota was also partially overspread with ice from the same Keewatin center. It pushed against the eastern edge of the Missouri Coteau in a similar way, but the coteau was more interrupted, or less continuous, so it did not offer the same resistance as in North Dakota. Moreover, it was moving in a river valley upon alluvial deposits, which no doubt made its progress more easy and rapid.

⁶ Third Biennial Report of the North Dakota Geol. Surv., pp. 80-86.

⁷ Journal of Geology, vol. 23, pp. 53-55.

From these facts it will be readily seen that the principal relations of the Missouri River to the ice-sheet would be very similar to those in North Dakota. The principal difference would be that the ice extended

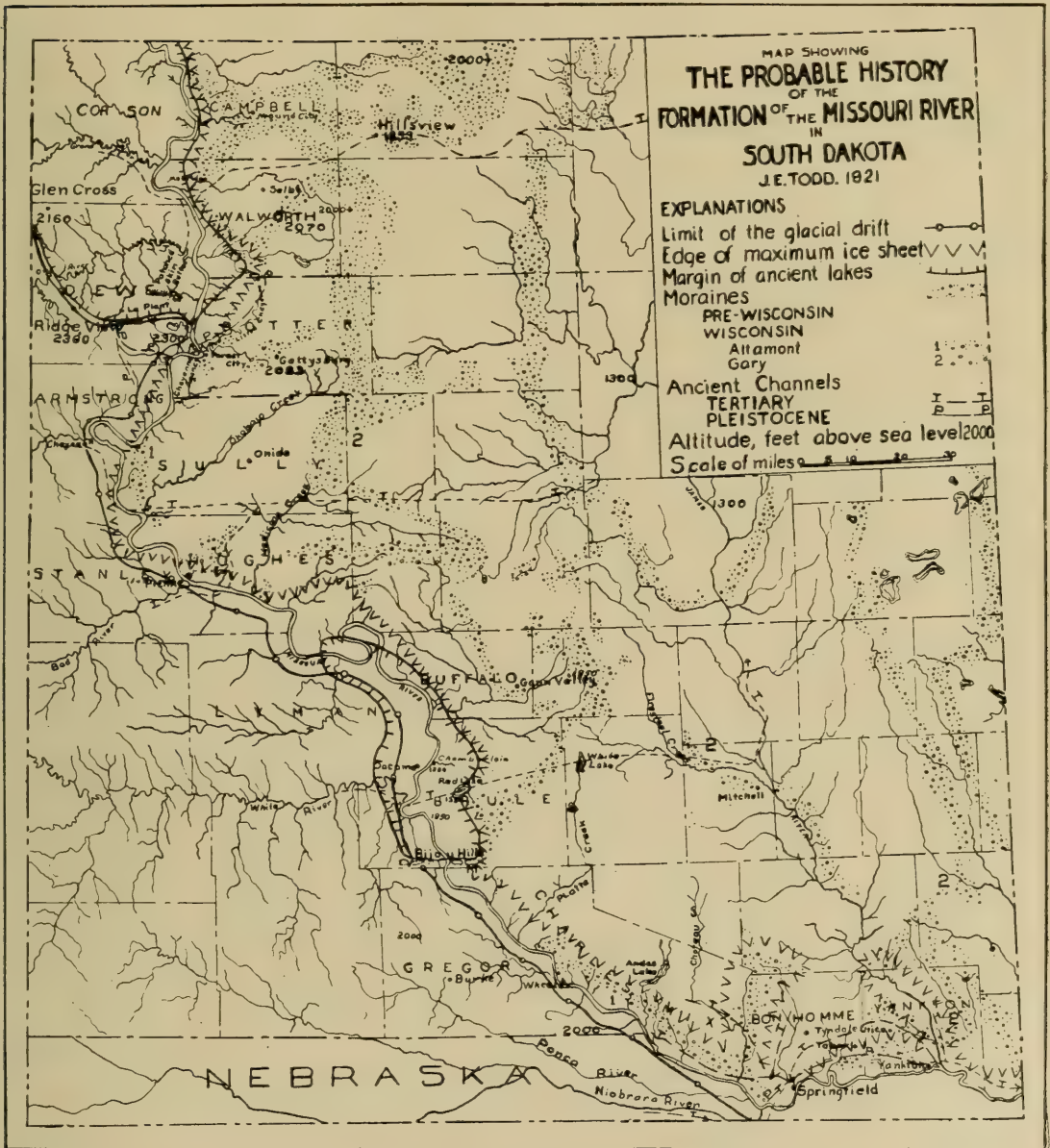


FIGURE 2.—*Map of South Dakota*

Showing probable history of the formation of the Missouri River in South Dakota.

so far south that it did not reach its maximum extent so soon, and the moraines formed would consequently be smaller and less continuous.

For our purpose, it will not be necessary to present all the evidence which might be stated. We will limit our discussion to two or three of the more decisive points.

DAMMING OF THE NIOBRARA RIVER

Some years ago the writer studied the ancient channels between the States of South Dakota and Nebraska. The older system included the Niobrara, Ponca, Mosquito, and Choteau creeks. Their altitude was from 100 to 125 feet higher than the present streams occupying that region. It is evident that the Niobrara, the larger one, crossed the trough of the present Missouri a little east of Springfield, swept in a broad curve to the north past the stations of Tabor and Utica and merged into the present course of the Missouri a few miles east of Yankton. This is shown not only by the topography, but by the deposits found in wells. When the extremity of the James River ice-lobe reached this old valley in the northern part of Yankton County, it forced the stream to find its way around the edge of the ice, and so located the present course of the Missouri between Bonhomme and Yankton. Judging from the exposure of bedrock in the sides of its new valley, it must have cut down in some places on the south side 200 to 350 feet. The level of water, as before stated, was more than 100 feet higher than the old level of Niobrara and its tributaries.

BIJOU HILLS DIVIDE

Near the southwest corner of Brule County, South Dakota, there is seen a prominent and nearly continuous line of flat-topped buttes, rising 300 to 500 feet higher than the surrounding country and about 2,000 feet above the sea. The line of buttes stretches away in the distance toward the west, and only two of the buttes are east of the Missouri River. It may have extended farther east and the ice may have carried them away. Lying up against the eastern end of the eastern butte is a ridge of till or boulder-clay. The till also comes up high on the southwest corner of the butte, but no northern boulders or pebbles are found on top of any of the buttes. Along the northern side of the butte, just east of the Missouri, numerous boulders are found, and apparently the upper limit of their distribution seems to mark an old water line. The height of this line is determined by a barometer for 1,880 feet above sea-level.

Opposite the mouth of the White River may be found trace of the side of an old channel, about 225 feet above the river, which may be traced more or less clearly to Red Lake and Pukwana, where it is 1,543 feet above sealevel. The Missouri River at low water at Chamberlin is 1,323. White Lake, in the northwest corner of Aurora County, seems also to be in this old valley, which without doubt extended to the James River. Between Pukwana and White Lake it is too deeply covered with boulder-clay to be traced clearly.

The conclusion from these facts seems simple and unquestionable. Before the Wisconsin ice came, White River flowed through this valley into the James River. When the ice dammed up the White River the waters rose north of the Bijou Hills until they found a way around east. Some trace of such a channel is marked by a shallow depression occupied by a string of lakes and lake beds. When filled with water, there are few places east of the Bijou Hills where it can be crossed. When this outlet was stopped by the farther advance of the ice, the water rose until it found an outlet along the line of the present Missouri River. Since that time it has cut down about 600 feet. This rapid erosion is greatly assisted by the soft and slippery character of the Pierre formation, which occupies nearly the whole height of the gorge (see figures 3, 4, and 5).

FOX HILLS DIVIDE

Lake Arikaree.—This is the most complete and complicated of all. As one approaches from the south, he sees stretching across the course of the Missouri River a high, massive highland. It seems to be nearly flat on top and somewhat higher toward the west, while eastward it becomes more broken, for it is well covered with glacial deposit. The higher portion west of the river was named by early explorers as Fox Ridge, although its top was nearly flat for a breadth of 10 miles. East of the river are prominent points in the Altamont moraine about Gettysburg. The southern side of this ridge is more abrupt than the northern, which is traversed on the west by Moreau River and by Swan Lake Creek; flowing west. The basin of the latter is limited in extent, but it must have been considerably higher to allow for the glacial erosion to which it was subjected without being reduced in height lower than Fox Ridge on the west. The latter rises to 2,300 feet within 10 miles of the Missouri River. East of the river are exposed points of older rocks, which reach a height of 2,000 feet, while the morainic points may reach 2,100 to 2,200 feet.

At the maximum stage of the ice, which had reached apparently little more than the Altamont moraine, the water derived from the Moreau and Grand Rivers, and other streams seeking their way around the edge of the ice-sheet, gradually filled the present valley of the Missouri north of Fox Ridge into a lake 30 or 40 miles wide and extending northward indefinitely. This hypothetical lake has been named "Lake Arikaree," after a tribe of Indians which occupied the region when first discovered.

Glacial Boulders without Till.—The main evidence of the former existence of this lake consists of the absence of glacial till west of the Missouri River and of the general distribution of scattered boulders over

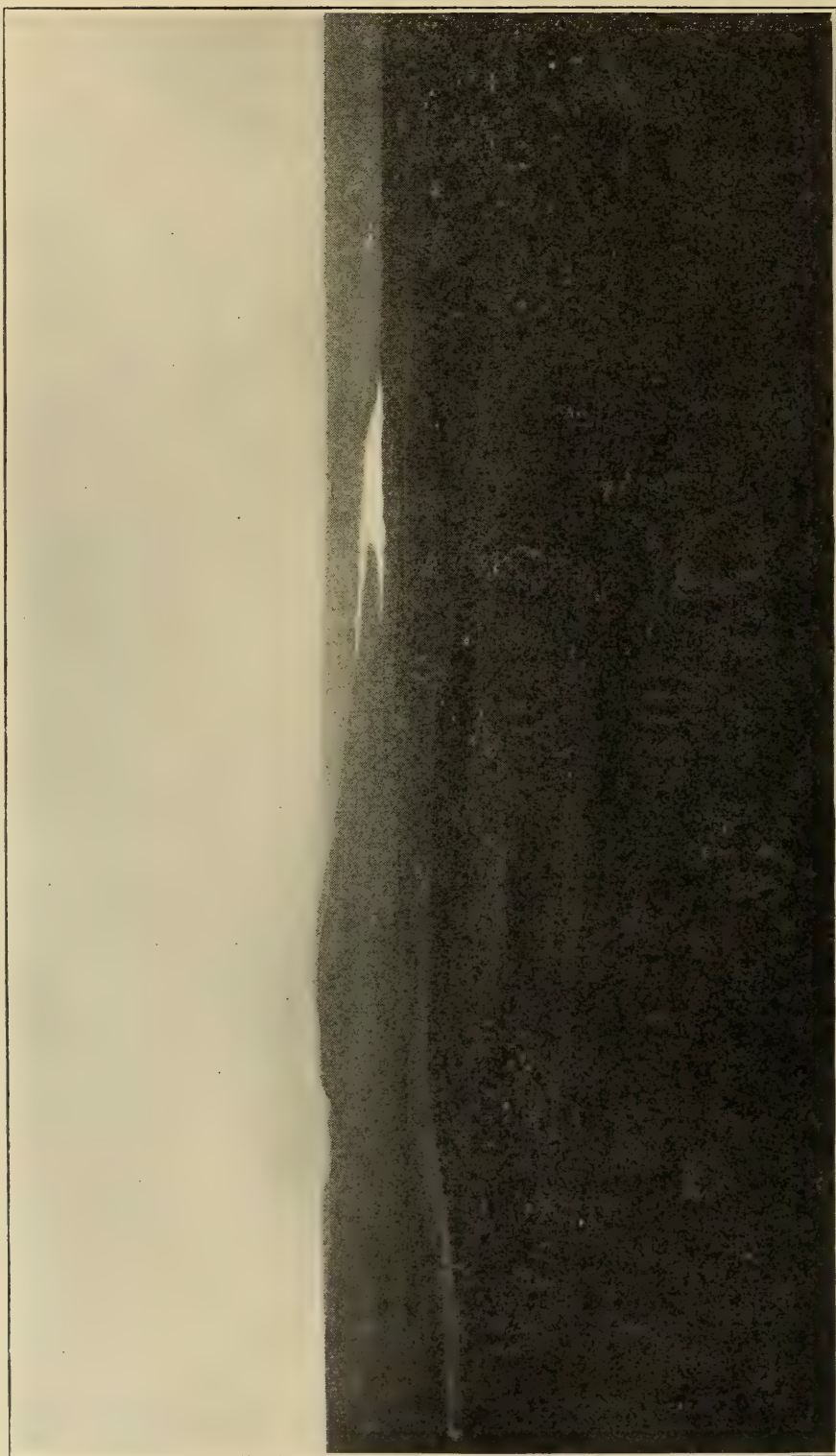


FIGURE 3.—*Bijou Hills and Gorge of the Missouri*

This view is taken from the summit of the hill about 5 miles northeast of the gorge. The summit of the farther butte is about 800 feet above the river. Its structure is of Pierre clay, except 25 or 30 feet of Tertiary sandstone on top. The peculiar tendency of the clay to landslides may be seen on the slope between the butte and the river.

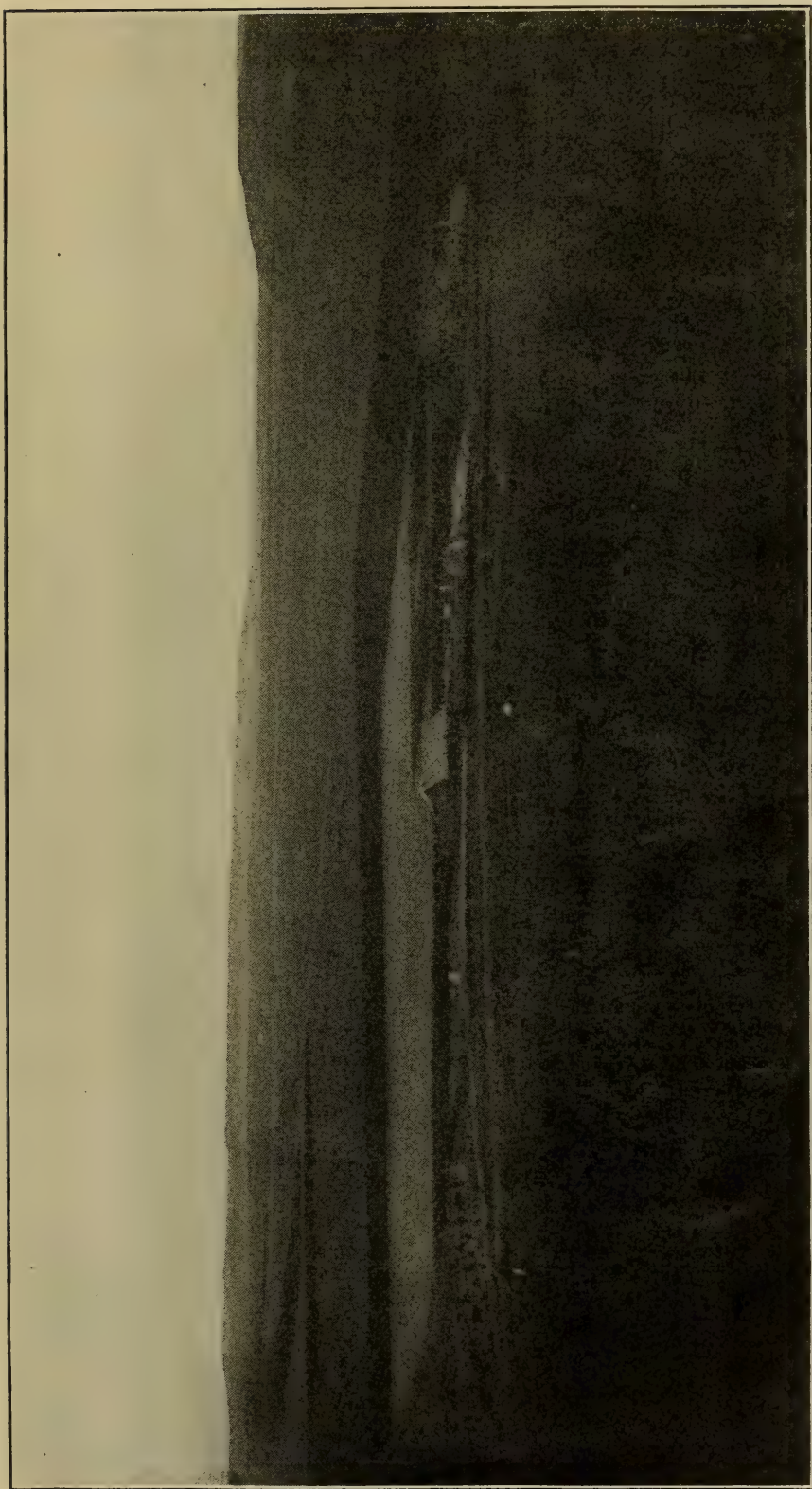


FIGURE 4.—*View of East Bijou Hill, Part of West Bijou, and the Gap between.*
This view is taken from the northwest, from the same point of figure 3 and nearly joining it.

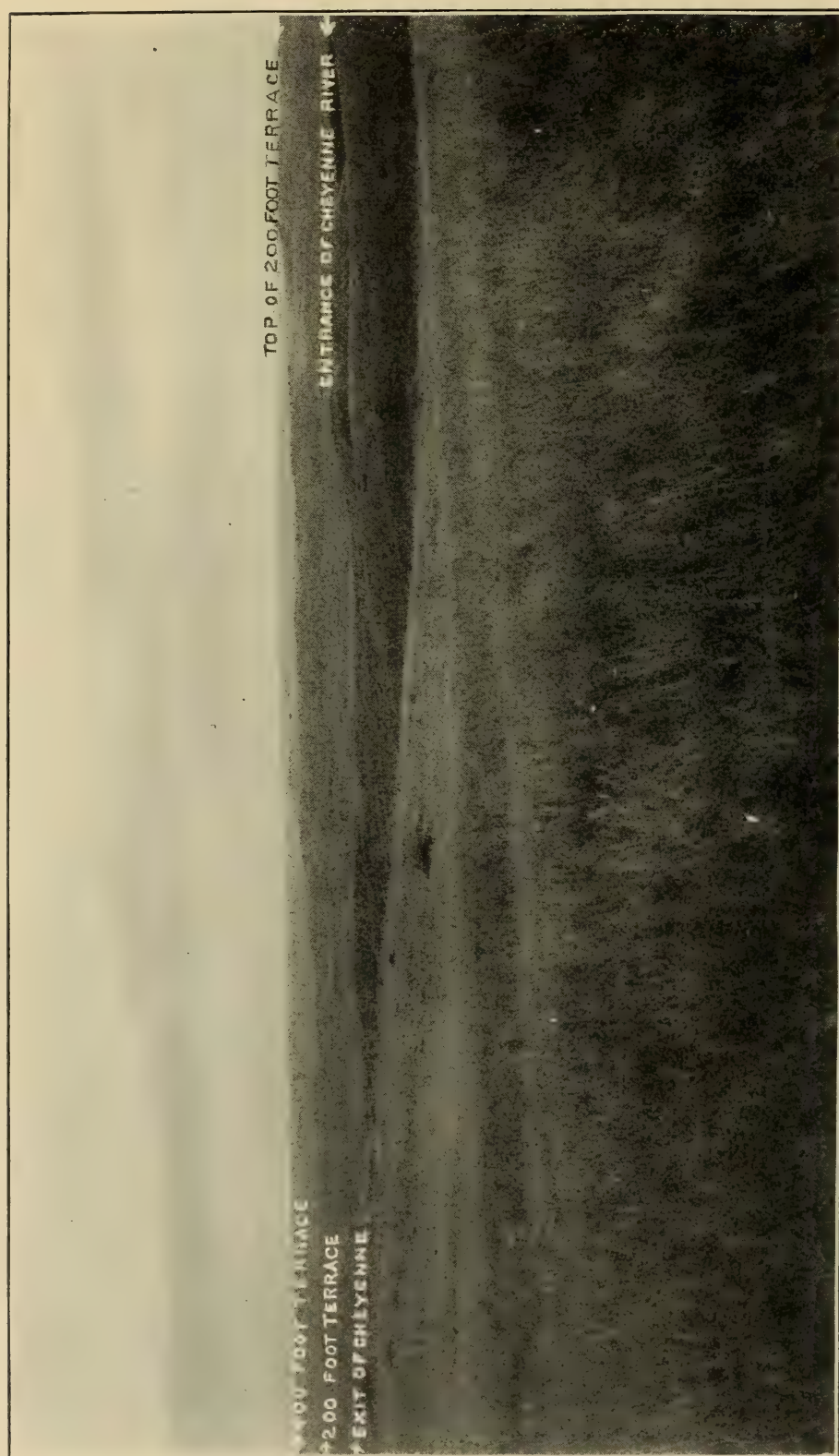


FIGURE 5.—*Panoramic View of the lower Cheyenne River, looking Southwest from the Upland North of its Mouth*

The arrows indicate location of the upper terraces, about 490 and 200 feet respectively above the river. These terraces are very broad, in some places 4 or 5 miles. It is believed that they have been formed since the present location of the Missouri River or since the beginning of the Wisconsin Stage.

the basin. In the vicinity of Virgin Buttes boulders are found rising to the level of about 2,200 feet. On the north slope, south of the Moreau River, evidence of a similar altitude is found by the occurrence of similar northern boulders capping Patched Skin Buttes. What seems inconsistent is the fact that south of the Patched Skin Buttes no drift boulders are found over a considerable area of less altitude. The extent, also, of this driftless area on the south is surprising in its narrowness and the fact that it is more than 100 feet lower than the Patched Skin Buttes.

But the flat-topped, rick-like buttes, apparently marking an old shoreline, were not all covered with boulders and much of the old shoreline was not marked by these buttes, but, on the contrary, the surface was gently undulating, very similar to glaciated surface. Such a case was noticed 6 or 7 miles east of Timber Lake. Approaching it from the west, no boulders were found until coming into this gently undulating topography and overlooking an apparent depression on the east, where boulders were plentiful and the surface had a very close resemblance to till topography. Here, again, there were traces of erosion which had carried the boulders toward the adjacent watercourses. Fortunately, there had been recent grading of an automobile road, which exposed a section from the surface down two or three feet and for many rods in extent. From these exposures it showed very clearly that the boulders were scattered on a surface of residuary clay or of Pierre or Laramie clay, but very certainly not any glacial till. Moreover, upon the elevations the boulders were not more than half submerged in the soil, while in depressions the boulders were in some cases completely covered with soil. The elevation of the top of the boulder-capped buttes and of the moraine-like surface seem to be at the same level. The boulder-capped buttes lie west of La Plant, extending several miles. The upper limit of the moraine-like surfaces at other points did not rise above 2,155 feet.

Outlets.—Another evidence of the former existence of Lake Arikaree is the finding of outlets. We have already spoken of the driftless character of the surface lying west and south of this lake and of the abrupt appearance of numerous boulders when a certain level was reached which might be supposed to be the boundary of the lake, the margin or water level. Around the Cheyenne Indian Agency near Forest City the surface northward is without boulders as soon as the level of the highest river terrace has been passed. The surface is very much eroded and composed largely of Pierre shale. About 10 miles west of Cheyenne Agency one suddenly comes upon the valley of Stone Creek, which is named from the abundance of northern boulders found in the valley. The bottom of the valley is not very clearly the course of a stream, for erosion has changed

its surface very much. Its bottom is composed of low knolls elongated with the axis of the valley, and usually with abundant boulders, especially upon the summit, as if a stream bed had been unoccupied for a long time and erosion had removed most of the fine material. This channel passes over the divide between Stone Creek and a branch of Virgin Creek which leads north-northwest, east of La Plant. The bottom of this channel east of La Plant is at an altitude of about 2,000 feet.

Of course, one outlet corresponds with the present course of the Missouri River. There are points near Welland, east of the Missouri River, which rise to more than 1,900 feet, or 500 feet higher than the Missouri.

Another channel, which probably had served as an outlet before the glacier had covered it in its advance westward, has a general south-south-east course, passing a little east of the northwest corner of town 120 north, range 76 west. It extends for 7 or 8 miles, from the breaks of Swan Lake Creek to the valley of the Little Cheyenne.

The order in which these outlets served was, first, the eastern one, leading into the Little Cheyenne; second, the Missouri as now located; and, third, the western one, which probably was the main one in the earlier and higher stages of the lake. It had probably cut down 100 to 200 feet before the recession of the ice uncovered the present course of the Missouri, which has been occupied ever since. The maximum extent of the ice was in the formation of the Altamont moraine, of which portions toward the south are found in the Artichoke Hills and Sully Buttes.

The edge of the ice must have been very near the present river, probably covering, but not extending at any time to, the third, or Stone Creek, outlet. The region between the present course of the Missouri and the old Stone Creek outlet is driftless, so far as has yet been discovered, at least 10 or 15 miles north from the Cheyenne Agency. This area does not seem to be much higher than the region farther north; and yet we must conclude that this area, at the time of the highest stage of Lake Arikaree, must have been 100 feet higher than at present. It is not difficult to suppose that there has been time sufficient for the carrying away of such an amount of material by erosion, for the Pierre formation occupies the whole height of six or seven hundred feet and there are numerous deep ravines running southeast parallel to Stone Creek. The Pierre formation is almost pure clay and very subject to landslides on steep slopes, especially when the base is softened or eroded by running water. The whole surface of the bluffs of the Missouri River opposite the Cheyenne Agency, for a height of 250 to 300 feet, is covered with sliding masses 50 to 150 feet wide.

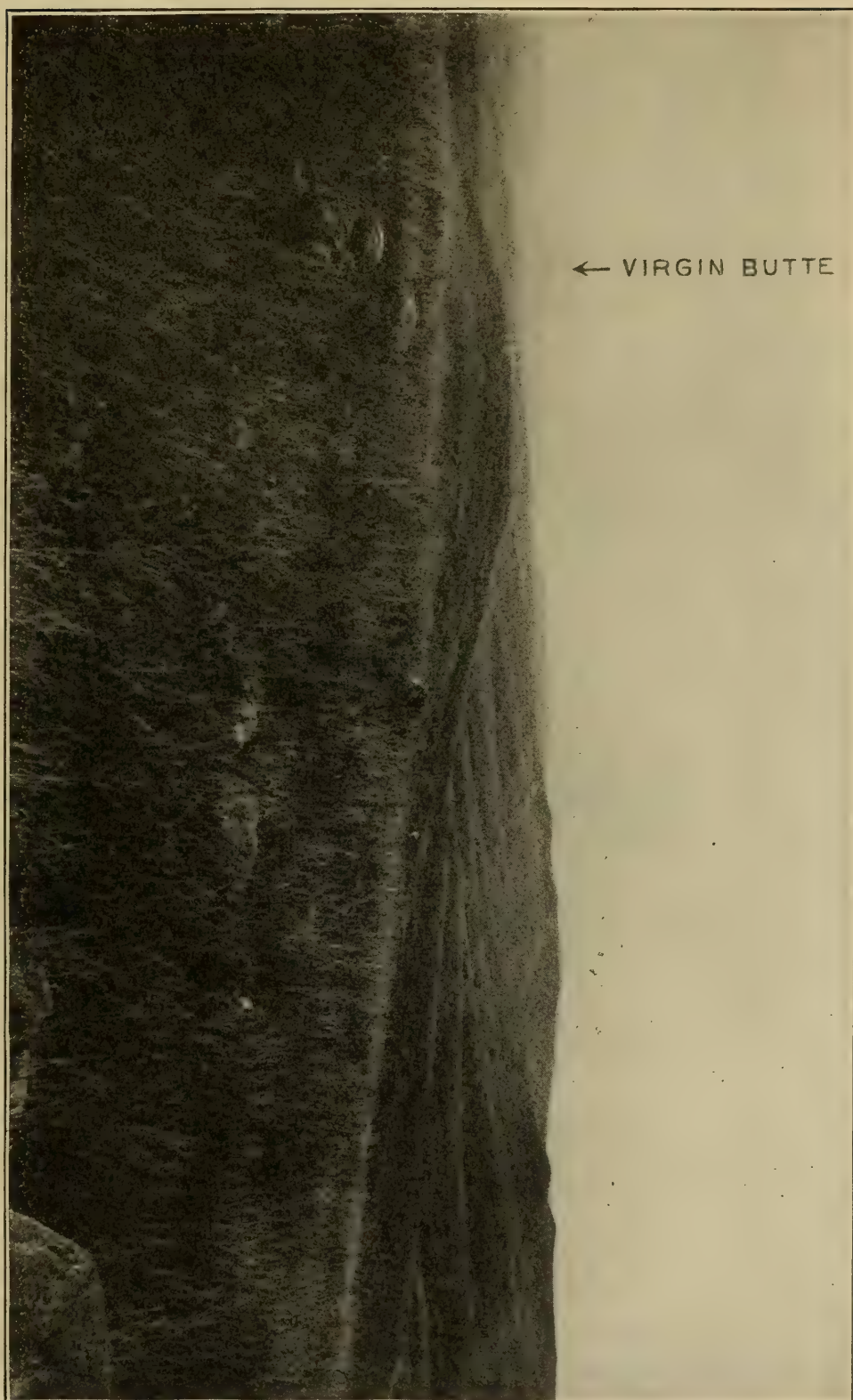


FIGURE 6.—*View of Portion of bouldery Margin of Lake Arikaree, with Virgin Butte in the Background*

The view is looking a little north of east. Just beyond Virgin butte is the old outlet which formerly drained Lake Arikaree down the valley southeast, now occupied by Stone Creek and Virgin Butte Creek. The country to the right and back of the river is almost strictly driftless. There is a gradual rise farther south into Rox Ridge.

EVIDENCE FROM MONTANA

GENERAL STATEMENT

The Missouri River in its course throughout that State has been related to the ice-sheet on the north and the driftless regions on the south, similarly to that which we have noted in North Dakota and South Dakota. Moreover, the history of the ice-sheet seems to be very similar to that in North Dakota. There is found in both cases till-covered areas outside of the Altamont moraine. This till may be of Kansan age or of early Wisconsin. The most recent stage of the ice was that of the Wisconsin at the time of the formation of the Altamont moraine. This general relation is similar to that which we have recognized in South Dakota and of course argues that similar might be expected in North Dakota, the State between.

That the valley was Tertiary is indicated by the geological section at Glass Bluff,⁸ 4 miles southeast of Buford. "Glacial drift, 25 feet," lies more than 160 feet above the Missouri,⁹ or 2,100 feet above tide. This agrees well with the "Benny Pierre-Hay Draw" outlet, 2,200 feet above tide. Afterward the Yellowstone became a component of the Missouri and cut down its present channel.

POSTGLACIAL EROSION

Dr. Leonard has concluded that the erosion of the Missouri River along its present course is too great to have been accomplished by that stream since the beginning of the formation of the Altamont moraine. The erosion at its greatest is not more than 500 feet in depth and a mile or two in width. From Montana we find that the erosion from the Missouri channel from Mussel Shell River to Milk River is from 600 to 1,000 feet. In the former case the material eroded is mostly clay and soft sand. In the latter it is consolidated sandstone. Below Great Falls the Missouri has been flowing over sandstone, so that it is readily seen the postglacial erosion is 150 to 250 feet in depth. Another point is that the preglacial valleys in a number of cases, especially toward the west, are cut very much deeper than those of postglacial origin. This is prominent in the case of an old channel of the Missouri near Great Falls, which by boring near Sand Coulee was found to be 270 feet deep.¹⁰

DIFFICULTY OF REMOVING DRIFT FROM CHANNELS

From the map on page 38 we see how the erosion of a drift-filled channel seems very little, if any, affected by harder rocks for the walls of the

⁸ Third Biennial Rept., N. Dak. Geol. Surv., p. 19.

⁹ Bull. Geol. Soc. Am., vol. 27, p. 300.

¹⁰ U. S. Geol. Surv., Professional Papers, No. 50, p. 36.

valley.¹¹ How much less, therefore, when both walls and filling are unconsolidated, as in most of the Dakotas.

*THE YELLOWSTONE AND LITTLE MISSOURI DIVERTED FROM THEIR
TERTIARY CHANNELS*

Mr. Calhoun, from a study of the Keewatin deposits in Montana, traces the preglacial valley of the Missouri to Glasgow, on Milk River, and from quotation from others shows that it continues on to the northeast corner of Montana, and the Little Missouri likewise shows similar points in its history.

"In the late Tertiary," according to C. M. Bauer,¹² "it occupied a well-marked channel extending northward from the first prominent eastward bend of the present stream to the head of Tobacco Garden Creek and thence along this valley to the present Missouri," he adds, "to the Tertiary Yellowstone near Williston." More likely the Tertiary Little Missouri crossed the Missouri near the mouth of Tobacco Garden Creek and ran north several miles farther before reaching the Yellowstone.

During the maximum of the ice all three streams joined in a lake and for a time flowed eastward over the mid-course of the smallest stream. Eventually the Yellowstone and Missouri ceased to rise to Benny Pierre-Hay Draw outlet, but found the course of the present Missouri River, the Little Missouri determined by an outlet of the lake. The Missouri and Yellowstone, on the withdrawal of the ice-sheet, found themselves in well-defined valleys from Poplar and Glendive respectively to Williston. The most plausible explanation of the new channels is that they were eroded by subglacial and preglacial streams during the advance, the culmination, and earlier recession of the early Wisconsin. Head erosion we deem to have been particularly efficient during the recession of the ice. It was a time of rapid deposition of stratified drift.

SUMMARY OF EVIDENCE

All of the arguments presented by Dr. Leonard for the origin of the channel of the Missouri as being preglacial or Tertiary are found to be negative or indecisive. In other words, the case as he presents it is not proven.

The first positive argument for the glacial and Pleistocene origin of the Missouri channel is the evident relations of the latter to glacial distribution and deposits. This argument is especially strong if no other theory is capable of explaining the facts. Dr. Leonard gives us no reason

¹¹ U. S. Geol. Surv., Professional Papers, No. 50, p. 31.

¹² Journal of Geology, vol. 23, p. 55.

for the anomalous relation of the Missouri to the general slope of the country, namely, that the general course is nearly parallel with the strike of the slope of the surface instead of with the dip. This argument will stand, and the burden of proof lies on the other side.

The presence of stratified drift in the higher portions of the valley, together with the absence of till at lower levels of same, is strong evidence that the valley is glacial or postglacial in formation. If streams flowed at higher levels, they show the altitude of the plane of drainage at that time, and the absence of till at lower levels proves that the lower portion of the valley was not excavated; for we can not conceive of the lower portion being filled with drift, especially till, and later have it all removed. The very nature of the case forbids it.

An analogy with the cases studied in South Dakota and Montana strongly argues for the Glacial or Pleistocene origin of the valley of the Missouri in North Dakota also.

PROVISIONAL HISTORY OF THE ORIGIN OF THE MISSOURI IN NORTH AND SOUTH DAKOTA

GENERAL STATEMENT

In this portion of the course of the Missouri it is crowded by the edge of the Wisconsin ice-sheet on the left from near its origin in Montana to the southeast corner of South Dakota. On its right side there lies an area over which the Wisconsin ice-sheet never passed. From Niobrara eastward, where the river forms the boundary of the State, there is a till-sheet formed by an older ice-sheet which extends over many square miles southward into northeastern Kansas. This is known as the Kansan ice-sheet, which is judged to be much older than the Wisconsin.

In South Dakota no boulder-clay or till has been found west of the Missouri, although it is not unlikely that closer search may show considerable of the Wisconsin till outside the Altamont moraine. In North Dakota there are a few small patches of till lying 40 or 50 miles to the west or south of the river. In northeastern McKenzie County a portion shows not only patches of till of moderate thickness, but also distinct moraines. In the western part of Montana, near the Highwood Mountains, there is a moraine 50 to 100 miles in length and so continuous as to change the course of streams in the vicinity.

The general course of the moraines, both older and newer, is northwest. Dr. Dawson, of the Canada Survey, considers the older drift deposits and moraines next west of the Wisconsin stage in Canada to be Iowan. Tyrell, of the same Survey, considers them Kansan. Calhoun considers

the older deposits there to be early Wisconsin.¹³ Leonard considers the older drift in North Dakota, especially that west of the Missouri, as Kansan, but also recognizes till east of the Missouri, outside the Altamont moraine, to be early Wisconsin.

It seems not improbable that some of the morainic drift west of the Missouri belongs really to the early part of the Altamont moraine, as, for example, in eastern McKenzie County. It is generally agreed that the ice which was concerned in this case was also from the Keewatin center west of Hudson Bay, and that it was of the Wisconsin stage; and it seems probable that considerable of the drift outside of the Altamont moraine is to be included also under the term "early Wisconsin," and that the great prominence of extra morainic till in Montana, and to a less degree in North Dakota, is to be attributed to the lower temperature of the ice at that higher latitude.

GLACIAL ACTIVITY INCREASES WITH TEMPERATURE

A principle that is generally recognized is that higher temperature promotes greater activity in glaciers—that is, that the velocity is much greater in summer time than in winter time. Moreover, much more water is discharged in all streams supplied with water from the ice, forcing them to put on a torrential phase with maximum. A corollary from this principle would be that glaciers on the south tend to receive more heat, and consequently move more rapidly on that side. For somewhat similar reasons glaciers seem to be more active on their south and west sides because of the greater influence of the sun's heat.

DURING THE ADVANCE OF THE WISCONSIN ICE-SHEET

It will be readily seen that, so far as North and South Dakota are concerned, the ice approaches them from the northeast, and it is evident that it must have moved more rapidly in a southward direction; so that it may have, perhaps, reached the southern line of South Dakota nearly as early as the western part of Montana, and that its appearance opposite the angle northeast of Bismarck may have been considerably earlier than at the points already specified. At any rate, we may suppose that the age of the Altamont moraine is about the same throughout, although older portions—that is, near the outside and at higher levels, unless apt to be removed—may have been accumulating hundreds or thousands of years earlier than the inner portion of the same moraine.

Previous to the formation of the Altamont moraine, we may suppose that the valleys of all streams flowing north or east would become ob-

¹³ U. S. Geol. Surv., Professional Papers, No. 50, p. 52.

structed or dammed by the ice and changed into lakes, which would fill rapidly, not only from the glacier, but from the rainfall of regions farther west; so that in a short time each prominent river basin would contain a good-sized lake. Because of the eastward slope of the country, these different lakes would become deeper first next the ice, and the connecting streams escaping from the lakes would be first in the close vicinity of the ice. We may suppose that the line of lakes in both of the Dakotas would have several phases of development with each particular stage, but more or less contemporaneous through them all; and yet it would take longer for a large lake to pass through certain stages than a smaller and simpler one.

THE NIOBRARA RIVER AND RED LAKE

In the early stoppage of the stream we may suppose that the Niobrara River and Red Lake may have developed more promptly, although they may have begun later than the lakes farther north. They were able to cut through their respective barriers more promptly, and thus prepare the way for the draining of the lakes farther north.

It is probably unnecessary to attempt to give the lakes in detail or in order, referring instead to the maps and remembering that the phase during the old history must have changed frequently. It may not be necessary to do more than call attention to some more striking points.

We find evidence that the Yellowstone and the Missouri west of the Little Missouri became dammed by the ice on the north, which caused an overflow into the valley of the Little Missouri. Leonard has assumed that the valley of the Little Missouri was Pleistocene, whereas we take it that its Tertiary channel was by way of Tobacco Garden Creek and northward until it found the Yellowstone. When the ice advanced, it dammed the course of the Little Missouri and formed a lake, which received water for a time from the Missouri River and the Yellowstone through the Benny Pierre-Hay Draw outlet.

The outlet of Little Missouri Lake was along the present course of the Little Missouri eastward. Patches of numerous boulders are found here and there marking the course of the Little Missouri around northeast and south of the Kildeer Mountains. Probably at its early stage it emptied into Knife River Lake, this lake in turn passing over into Heart River, and so on southward into Lake Arikaree. An old shoreline of this lake seems to have been the origin of Farmers Valley and of the escarpment south of it. As the lakes had their outlets cut down more and more, one marked effect would be that these outlets would be on the side next the glacier, for not only would the slope of the country tend to throw them farther east, but also the streams on that side would be much more

active and prevalent, and therefore their head erosion much more rapid. Eventually the lakes became less extensive, and as the ice withdrew to the east again the lakes in general would become filled and drained until they disappeared. The effect of the ice withdrawing to the eastward would be to uncover more lake area lying adjacent to the front of the ice.

The explanation of the larger streams lying not far from the permanent and larger moraine, known as the Altamont, is to be found in the principle already mentioned, that the head erosion is particularly active in the streams immediately supplying water from the ice. This explains why the present course of the Missouri was located quite early. This became permanent before the withdrawal of the ice from the Altamont moraine. In short, the waters from the moraine eroded quite rapidly, because the coarse material was dropped next the ice, so that erosion was accelerated at a short distance outside of the main deposition. We conceive of the Missouri cutting down deeper and deeper during the Pleistocene, excavating what Dr. Leonard has called "the preglacial valley." This reminds us of a point of which we have said little, but which in its combined effect serves as a powerful argument for the similar origin of the Missouri in all three States under consideration.

TERRACES

In the valleys of the Missouri and its principal tributaries, there are many very striking river terraces. These terraces are mainly the result of erosion, the lower part of them being composed of bedrock and the top composed largely of coarse material, mainly from glacial drift, the finer silty material being largely washed away. A general statement applying to all these terraces may be given as follows:

They vary in altitude above the principal stream from 20 to 450 feet. Those lower than 20 to 40 feet show few boulders and are known as "silt terraces" or "second bottom." They probably mark the erosion which has taken place since the disappearance of the ice. Those above 100 feet are usually largely composed of boulders in the upper portion. These boulders are the larger and more conspicuous, from 200 to 300 feet. These upper ones are called "boulder terraces," and without doubt mark the intensity and altitude of erosion at different stages in the early Wisconsin stage. These terraces are as near level as usual under such circumstances, except for several miles below Bijou Hills, where some of the terraces show a much steeper slope down the stream. This uniform arrangement corroborates more strongly the idea that the history of the streams in these three States have been unusually uniform. Not only

does it emphasize the similarity of the conditions of the different streams, but the different areas are parts of the same system; so that we can not conceive of one portion being cut down without the subsequent lowering of all connected with it. Hence it is inconceivable that Lake Arikaree could have drained until Lake Niobrara had cut down; in other words, not before the Pleistocene. On the other hand, we can not believe that the valley of the Missouri in North Dakota could have been excavated or formed during the Tertiary without excluding the Yellowstone and the Little Missouri on the one hand or the Cannon Ball on the other.

We conceive that the erosion of the valley of the Missouri had cut down within 400 or 500 feet of its present level by the advance of the ice to form the Altamont moraine. This would correspond to the boulder-topped terraces spoken of in connection with the Little Missouri and elsewhere.

In the maximum extent of the ice, we find the time when the Pleistocene channels were first occupied—for example, the outlets of various lakes—and the lower boulder terraces mark the latest direct effect of the Altamont moraine upon the stream and its deposits.

HEAD EROSION PROMINENT

We have already alluded to the prominence of this function of streams, but we find it especially prominent in the history of this region. It has been especially the cause of the various streams approaching the Altamont moraine. While there may be traces of portions of the Tertiary courses of streams still occupied and later of Pleistocene courses, the portions of streams next the moraine which together form the present course of the Missouri have been formed by this action of streams, namely, head erosion. To illustrate, we have the Tertiary course of the Little Missouri marked from its eastward bend to the mouth of Tobacco Garden Creek. The course from the bend eastward would be of Pleistocene origin, probably during the maximum extent of the ice, and probably the earlier part of it was a lake which soon became drained. The course of the Missouri from the mouth of Tobacco Garden Creek to the present mouth of the Little Missouri would be an example which was formed by head erosion and was probably not continuous and prominent until the latter portion of the Wisconsin.

THE BIG BERTHOLD BEND

What seems a unique but unmistakable example of this is illustrated in the Great Bend in Fort Berthold Reservation. It has already been suggested by several observers of that region that the curve of the great U-shaped bend marks the position of a moraine formed around the south-

western tip of a local ice-lobe, and the straight valley reaching across the top of the U is the bed of the preglacial course of the stream, and that in some way this straight valley—which, by the way, is more than 100 feet higher than the present river and slopes downstream—became filled by ice in the advance of the glacier which formed a bridge for the onward motion of the ice. The suggestion is perhaps insufficient and presents several difficulties which we need not stop to consider. Meanwhile the water of the stream above the U found its easiest pathway to be around the outer rim of the moraine. The head erosion acted along the more vigorous course of the water, namely, the outside of the moraine, until they completely connected the channel below with the channel above this U-shaped bend. This is a very unusual example of head erosion, the general tendency being rather to cut off bends than to form them. A portion of the ice may have fallen below the pressure of the ice behind and remained stationary, like a boulder pavement, except the stationary lower mass was ice instead of till. The rest of the glacier passes on to form the moraine. One fact favorable to this view is that the cross-valley is at right angles to the direction of the ice movement or the course of the glacier.

In conclusion we note that from whatever direction we have approached the region we have been considering, we find that the present course of the Missouri River is more recent than the Tertiary and earlier than the end of the Pleistocene, or more definitely during the Wisconsin Stage of the Glacial period.

Moreover, we have been reading one of the most interesting chapters of glacial history, but let no one think that we have been reading the most interesting. We know no reason why the stream changes were not as numerous and striking in the Nebraskan or the Illinoian as we have found them to be in the Wisconsin.

MERGING OF CARLILE SHALE AND TIMPAS LIMESTONE FORMATIONS IN SOUTHEASTERN COLORADO¹

BY HORACE BUSHNELL PATTON

(Presented before the Society December 29, 1922)

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INTRODUCTORY

In connection with field-work undertaken for the Colorado Geological Survey the past summer in the vicinity of La Junta, Colorado, the author has had occasion to note a gradual transition or merging of two formations that heretofore have been considered as belonging to two different groups, the Benton and the Niobrara groups. The present communication is presented with the consent of the Director of the Survey.

In southeastern Colorado the Benton group is developed as three readily distinguished formations. The lowest of the three is the Graneros shale, with some 200 feet of gray to black shales. The highest, or Carlile shale, has usually about the same thickness and is likewise composed of dark gray shales, which at the top change to a yellowish sandstone of 20 feet thickness or over. The two are separated by some 50 feet of Greenhorn limestone. The Niobrara group has a twofold division—into the Timpas limestone at the bottom and the Apishapa shale at the top. The two together have a thickness of some 700 feet, of which 500 feet belong to the Apishapa and 200 feet to the Timpas. The upper 150 feet of the Timpas are composed of gray shales with occasional thin beds of white limestone. The lower 50 feet consist of massive beds of soft, almost chalklike limestone, one to two feet thick, separated by very thin shale partings. The contact between the basal limestone of the Timpas and the underlying top sandstone of the Carlile shale is usually very sharp.

¹ Manuscript received by the Secretary of the Society December 30, 1922.

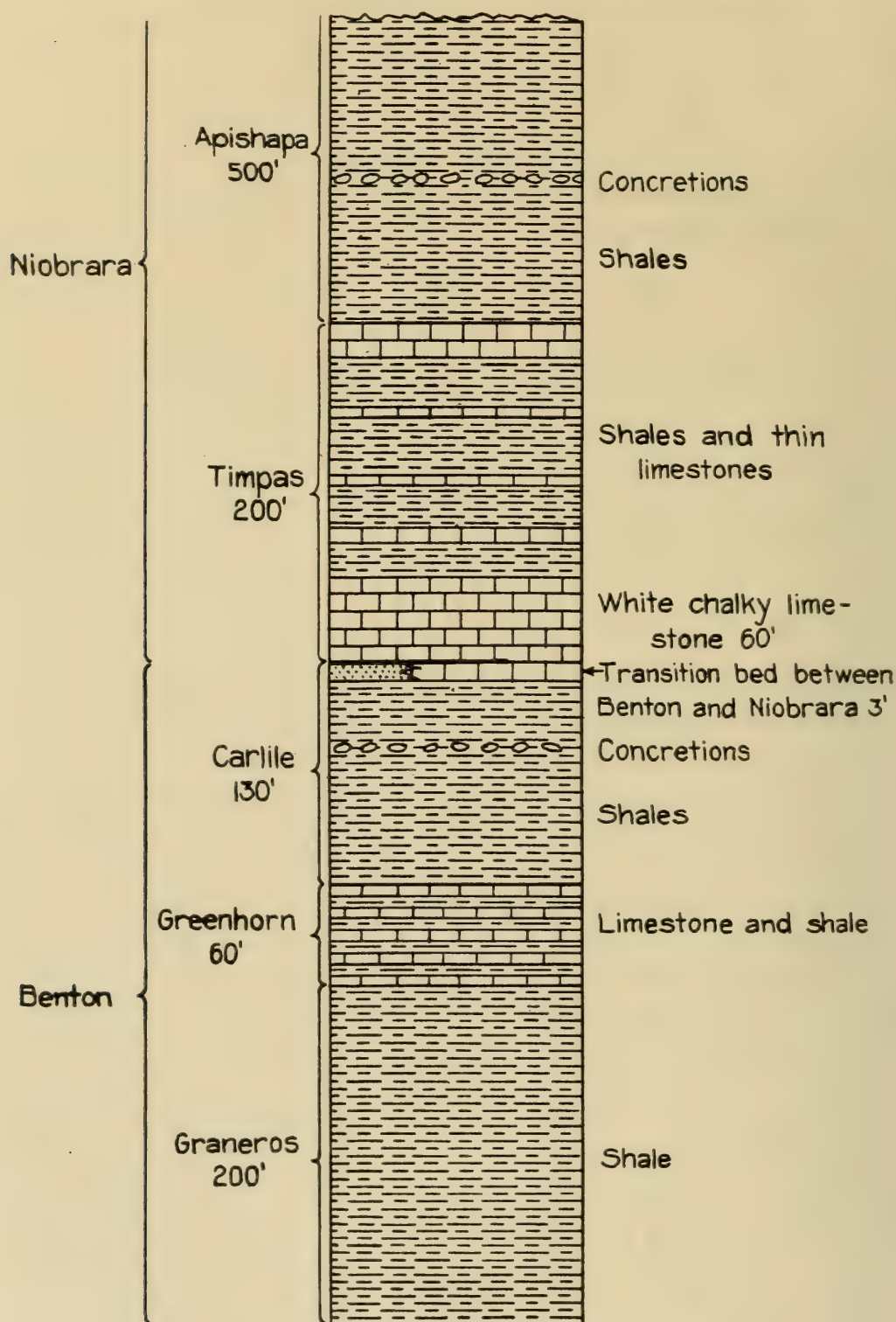


FIGURE 1.—Part of general Section in which Transition Bed occurs

THE UPPER CARLILE MEMBER

In writing of this Upper Carlile member, Darton² says:

"At the top there is a bed of sandstone varying in thickness from a few inches to 20 feet, the amount increasing to the west. . . . The top sandstone averages 10 to 20 feet in thickness west of longitude 104 and attains a maximum of 30 feet at Greenwood, on Hardscrabble Creek, and near Chandler, south of Canyon. Near La Junta it is three feet thick. . . . Usually it is soft, somewhat mixed with sandy shale, and of yellowish color. The fossil known as *Pugnellus* occurs abundantly in the formation in the southwestern portion of the area."

Writing of this same Upper Carlile member as it occurs in the Apishapa Quadrangle some 30 miles west of La Junta, Stose³ describes it as follows:

"In most places yellow sandstone 10 to 20 feet thick occurs at the top. The sandstone is calcareous in fresh exposure and is generally very fossiliferous in the upper part, its fragments being marked by casts of a large, strongly ribbed coiled ammonite, *Prionocyclus wyomingensis*."

This upper sandstone member thins out on approaching La Junta and becomes three feet thick or less. At the same time it loses its sandy character and becomes a crystalline limestone of grayish color that weathers to a dark rusty brown. It is also very fossiliferous, containing the same fossils mentioned above by Darton and Stose and including abundant *Ostrea* and occasionally sharks' teeth. Stose mentions the fact that the sandstone in the Apishapa Quadrangle in fresh exposure is calcareous. In the La Junta area it becomes altogether a limestone that is invariably crystalline. A typical sample of this rock dissolved in hydrochloric acid gave less than 1 per cent insoluble matter.

This upper limestone member is, in most of the La Junta area, sharply defined from the overlying Timpas limestone; but northeast of La Junta a change is to be noted. The rock loses in part its crystalline appearance and its uniform brownish color and becomes mottled white and brown. The irregular brown spots appear almost like inclosed fragments in the prevailing grayish white mass; but the frayed nature of the boundary line of these brown spots shows that they are due to local oxidation of the furruginous contents or to infiltration. At the same time the stratum loses its sharply defined upper edge and it becomes impossible to draw the line between this supposed Carlile member and the overlying white, chalky Timpas limestone. The two are apparently one.

² N. H. Darton: U. S. Geol. Survey, Professional Paper No. 52, 1906, p. 28.

³ George W. Stose: Folio, U. S. Geol. Survey No. 186, 1912, p. 6.

The above described characteristics are well shown at the base of the cliff on the south side of Horse Creek, in the northeast quarter of section 30, township 22 south, range 53 west, and they continue for 5 or 6 miles northeast of this point, which is as far as the field-work was carried.

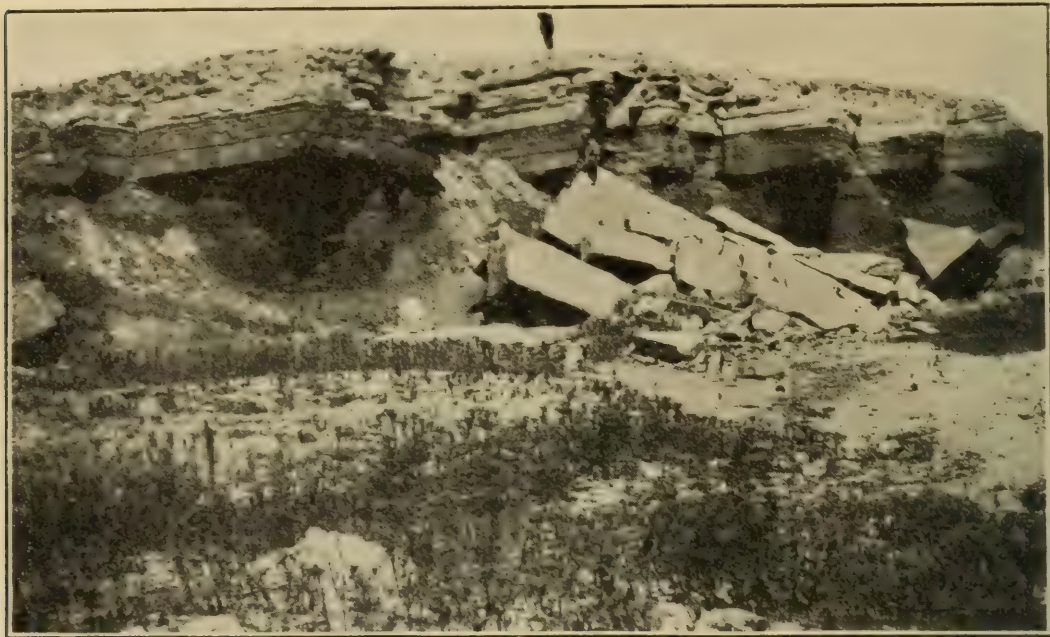


FIGURE 2.—*Contact of Timpas Limestone and Carlile Shale*

The contact occurs in Anderson Arroyo, about 7 miles south of La Junta. The photograph shows the soft black shale at bottom, the 3-foot brown limestone that marks the top of the Carlile shale in the middle, and the white, basal Timpas limestone at the top.

CARLILE FOSSIL IN THE TIMPAS LIMESTONE

In line with the observed merging of these two limestone members at the top of the Carlile and the bottom of the Timpas is the discovery of a recognized characteristic Benton fossil in the basal limestone of the Timpas. Near the center of the east half of section 27, township 22 south, range 53 west, and about 3 miles east of the location above given, a specimen of *Inoceramus* was collected near the base of the Timpas limestone. This fossil has been identified by Prof. Junius Henderson, of the University of Colorado, as *Inoceramus labiatus*, a form considered characteristic of the Benton group and very common in the Greenhorn limestone member of that group.

We have here, then, a case of a sandstone member thinning out toward the east and passing into a crystalline limestone, and the eventual merging of that limestone into the basal limestone member of a higher group. We also have, associated therewith, the passing of a typical fossil of the lower group up into the higher group.

GLACIAL LAKE PROBLEMS¹

BY GEORGE H. CHADWICK

(Presented before the Society December 30, 1922)

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LAKE WAYNE AND LAKE VANUXEM

Year by year the story of the Laurentian glacial lakes grows more complicated. The steadily falling waters of our youthful innocence are being replaced by a pulsating rise and fall due to rhythmic oscillations of the ice-front. One of these pulsations was long ago recognized by Fairchild² in his "free drainage" stage of lowered escape followed by the restoration of "Lake Vanuxem." Fairchild has frequently predicted that the real history would prove to be more complex than existing knowledge revealed.

Leverett and Taylor's recent exposition³ of the caprices of the ice on the thumb of Michigan instantly involves western and central New York, for the moment the water levels fell below the Grand River outlet they must go out by the Mohawk. The control channels of "Lake Wayne" must be sought at either Batavia or Syracuse.

Herein is introduced a new element in the recognized New York lake

¹ Manuscript received by the Secretary of the Society May 1, 1923.

² Bull. 118, N. Y. State Museum, p. 80; Bull. 127, N. Y. State Museum, pp. 50-59.

³ Mon. LIII, U. S. Geol. Survey, pp. 364-370.

succession. Hitherto it had been believed that the first of the Erie Basin waters to gain admission into central New York (the Genesee and Finger Lake valleys) was Lake Warren. In Fairchild's conception "Lake Vanuxem" stood as the earliest water body with easterly (Mohawk) escape, but he ascribed to Vanuxem no drainage from west of Batavia. Yet, if we correctly understand the relations, the episode of Lake Vanuxem and the "free drainage" interim is the only known place in the New York succession into which "Lake Wayne" can be fitted.

The admission of the Warren waters into central New York, past the Batavia salient, without conspicuous channeling on that salient presented a real problem to Fairchild.⁴ Practical coincidence of the merging water levels had to be subsumed. But if the Erie waters already flowed eastward, the restored Warren level would reach to Syracuse from its initiation and this particular puzzle be eliminated. Rather, the problem is pushed back to Lake Wayne, leaving the apparent absence of channels north of Batavia still a matter of inquiry. Possibly the control point is actually somewhat farther east, near Le Roy, where there are heavy channels just below the Warren beaches.

None of the Le Roy channels appears, however, to fulfill the requirements for the long-lived Wayne spillway. They conform to the temporary paths of waters rushing to a new confluence, not to a stabilized outlet. For that we must turn to Syracuse. Here we find at once a splendid channel at the right altitude (about 40 feet below Warren) hitherto unreferred to any fixed water plane. This is the "Gulf" west of Marcellus.⁵ It is confidently believed that the "Gulf" channel carried the Wayne waters prior to Lake Warren, and that it did not function again subsequent to the Warren flooding.

A curious fact concerning the "Gulf" remains, nevertheless. Below its intake it is distinctly depicted by Fairchild as a "two-story" channel (the only one he so represents), with the lower story much narrower than the upper, thus indicating diminished water flow. If this narrower inner channel were cut during the ice readvance following the "free drainage" stage, as seems likely, then the restored level ("second Vanuxem") would appear to have been robbed of the Erie drainage by readvance also at Batavia (or Le Roy?). This would mean that while "first" Vanuxem included the Erie flow from Wayne downward to its minimum stand and extinction in "free drainage," or even through the earlier rising levels of its restoration, there was no "restored Lake Wayne," but only local waters of the restored (incorrectly "second") Lake Vanuxem coursing

⁴ Bull. 127, N. Y. State Museum, pp. 51-52.

⁵ Bull. 127, N. Y. State Museum, pp. 26-30, pls. 4, 18, 19A.

through the "Gulf," while the Erie Basin waters were obstructed at Batavia and thrown back on the Grand River outlet as Lake Warren. This ice advance would obliterate the earlier channels at Batavia, but there is still the old difficulty of getting the Warren level eastward again past this point without a trace.

LAKE LUNDY (?) OUTLET

With the Wayne outlet at Marcellus (Syracuse), the fate of the Erie Basin waters during the "free drainage" interval remains to be considered. Following westward (upstream) the capacious channels of this stage, and noting their extensive delta deposits where they cross the Genesee and similar valleys, one is impressed with the belief that they carried more than local flow. At their upper end, north of Le Roy, the channel is a splendid rock-cut, over a mile long, a hundred feet deep, and a quarter mile wide. Its col appears to have been originally some 20 feet or more under the plane of the neighboring Dana beaches, but to have been somewhat silted up during the Dana stage.⁶ Back of this broad intake at Fort Hill, with present altitude about 680 feet, must have lain a huge lake, stretching to Detroit, hitherto unrecognized as such. Its close correspondence in level suggests that its beaches in the Erie Basin have been confused with those of the long subsequent Lake Dana. Spencer in 1894⁷ described the Lundy beach and once incidentally used the expression "the Lundy lake," a name which thus seems to have no standing as against the properly proposed and worthy name of Lake Dana, subsequently given by Fairchild to his Geneva beach.⁸ But should it appear on further study that the Lundy beach correlates with the Fort Hill channel, as is very possible, then both names will stand. Indeed, the Belcoda and other channels on the same meridian may eventually explain other features in the complex of beaches at this general horizon in the Erie Basin.

RESTORATION OF LAKE AMSTERDAM

During the "free drainage" stage the Mohawk Valley was necessarily unblocked at the east, giving passage to Fairchild's "glacio-Mohawk River." But Fairchild has shown⁹ that the east-leading channels of subsequent date from lowering Warren and Dana terminate east of Syracuse

⁶ See map, Bull. 127, N. Y. State Museum, pl. 2.

⁷ Amer. Jour. Sci., vol. 47, pp. 207-212. Said to be 25 to 40 feet out of harmony with Lake Dana, in U. S. Geol. Survey Mon. 42, p. 772.

⁸ Amer. Jour. Sci., vol. 7, 1899, pp. 260-1; Bull. Geol. Soc. Amer., vol. 10, pp. 56-57.

⁹ Amer. Jour. Sci., vol. 7, 1899, p. 262; compare also 20th Ann. Rept. N. Y. State Geologist, pp. 112 et seq., pl. 16; Bull. 160, N. Y. State Museum, p. 32.

(at Mycenae) considerably above the level of the Rome outlet, or higher than the free drainage channels. The inevitable conclusion is that they discharged into a restored Lake Amsterdam, due to reblocking of the Mohawk at its lower end (Schenectady). It is reasonable that any readvance of the ice at Syracuse sufficient to restore the Grand River outlet must have been accompanied (or slightly preceded) by a powerful thrust in the Hudson Valley, of which we here have the confirmation. Apparently this forward shove was felt also (a bit later?) at Batavia, thus sundering Warren and Vanuxem as above intimated.

EASTWARD REACH OF LAKE ARKONA

More puzzling questions revolve around earlier reexpansions of the ice. Taylor thinks that Lake Arkona invaded central New York before the readvance extinguished it. The position of the overriding Alden moraine in the wider portion of the Genesee Valley (where the Warren beach is strong but single), and thence eastward to the Seneca Valley, is well above the Warren level and shows that the ice must have there destroyed any Arkona beaches, except far south up the valleys, where they would necessarily be weak. Careful search may yet reveal these; probable beaches and notches occur, 20 feet above the Warren shore, at and east of Genesee, but the best record is found in the large 850-foot delta terrace at the mouth of the Mount Morris canyon, which could not have been built in Warren waters, because the canyon had been cut far back and deepened in the stage of lowered escape preceding Warren. The fact that the moraine of readvance barely sunders the Mount Morris and Newberry levels at the critical points near East Bloomfield, Reeds Corners, and Gorham is evidence that even Newberry had been swallowed down into Arkona before that readvance occurred. (See the chart, page 506.)

WESTWARD REACH OF LAKE NEWBERRY

In his later writings and maps¹⁰ Fairchild carries Lake Newberry into the Genesee Valley from the east at this same moment in the history preceding Lake Hall. While the overriding ice has destroyed the records, making it impossible to say that Newberry did not have such an extension prior to Arkona, yet it seems to the writer unlikely that the Newberry level entered the Canandaigua Valley before its restoration, and not immediately even then, being momentarily excluded by a restoration of the Potter Lake with new outlet east of Gorham. This presently fell to Newberry, and when the latter almost immediately coalesced with the

¹⁰ Bull. 106, N. Y. State Museum, p. 32; Bull. 127, N. Y. State Museum, pl. 35; etc.

Genesee waters these were at the Pearl Creek outlet, so exactly coincident in elevation that a divided escape ensued until the unblocking of the Linwood channel established Lake Hall.¹¹ It should be noted that Hall thus becomes a fairly fixed water body, not a series of lowering stages, though it may have been let down once, some 20 feet, to the Stafford channels.

A NEW GENESEE LAKE

Studies now proceeding on the complicated history of the Genesee Valley lakes indicate that Lake Dansville was admitted into the Canandaigua Valley by way of the Hunt Hollow strait following Lake Naples, and was then lowered down on this pass, instituting a new member in the Genesee succession, here named the "Livonia Lake." By opening of the Bethany channels Livonia became the Mount Morris falling waters, whose intricate history involved one more brief escape to the Canandaigua Valley by the Cheshire channels, as well as temporary separation from the Wyoming Valley by lowering on the Pearl Creek outlet channel.

HUDSON VALLEY LAKES

Greater interest attaches to the behavior of the Hudson-Champlain Valley during ice-waning. Woodworth's interpretation¹² of this behavior involved a peripheral bulge and a wave of uplift. Fairchild, whose early conception of the uplift as a rigid tilting was opposed to Woodworth's, has found independent evidence of the peripheral bulge in his work on the Susquehanna River.¹³ Antevs, Daly, and others assert the existence of the bulge and of lakes restrained behind it. Of these lakes one must have occupied New York Harbor and its environs, perhaps continuous with that in Long Island Sound; for this the name "Lake Manhattan" is here suggested. As the ice waned and the pursuing bulge raised Manhattan, the Tappan Zee would have held a water body which we may call "Lake Haverstraw." Perhaps even a third stage, north of the Highlands, preceded the inception of Lake Albany, and this might suitably be called "Lake Newburgh." The writer finds it difficult to conceive that any of these waters were salt, or with marine organisms.

LAKE VERMONT AND LAKE EMMONS

It becomes necessary at this point to reinstate Woodworth's Lake Vermont, for, like the preceding, this was sundered from the tides by the

¹¹ Bull. 106, N. Y. State Museum, p. 33, pl. 6.

¹² Bull. 84, N. Y. State Museum, pp. 229, 232.

¹³ Science, n. s., vol. 57, no. 1465, p. 113.

migrating bulge. That it had no free communication with salt water via the Hudson Valley is an inevitable corollary of Fairchild's discussion of the Round Lake region.¹⁴ Analysis of that paper shows that long before the unblocking of the north end of the Adirondacks, while still Lake Iroquois was discharging through the Mohawk and cutting the Round Lake channel, the Hudson Valley at that point had lifted so far as to confine the Hudson River to the narrow trench it was reexcavating in the clays of the Lake Albany filling. Lake Albany was gone. There was no open strait of salt water (or any other water) from New York to Plattsburg, but a river of fresh water flowing (with a gradient) southward and holding Lake Vermont to superoceanic level. The true marine waters (Hochelagan Sea) entered the Champlain Valley only when admitted from the northeast, past Quebec. By the original definition "Gilbert Gulf" is the portion of these marine (tidelevel) waters confined to the Ontario Basin, and the name should not be extended over the region in which Woodworth's "Hochelagan Sea" has clear priority.¹⁵

The Vermont beaches are finely developed at 740 feet above tide and down, both around Covey Hill and far into the Ontario-Saint Lawrence Valley. The true marine beaches are those originally recognized as such from 523 feet above tide down, on Covey Hill. Between these two sets is a gap of nearly 100 feet, marking the elevation of Vermont waters above sealevel just prior to their extinction.

Above the Vermont beaches, between them and Iroquois, in the Ontario-Saint Lawrence Valley, lie the "Emmons" beaches of Fairchild, rediscovered and renamed "Frontenac" by Taylor.¹⁶

THE ALGONQUIN LAKES

However intricately interwoven may be the Algonquin beaches, in point of historical sequence there are several distinct water bodies at present passing under the name "Lake Algonquin." Leverett and Taylor discriminate (1) an "early Lake Algonquin" confined to the south end of the Huron basin, with Detroit (that is, Port Huron) outlet; (2) doubtfully a tripartite lake with outflow divided past Detroit and Chicago, which seems to be an expanded Lake Chicago; (3) the true Algonquin, tripartite, with Trent River escape, and (4) the second Algonquin, restored to Port Huron outlet. To avoid confusion of speech, it is suggested that the first stage be called rather the primitive Huron, and that

¹⁴ Bull. 195, N. Y. State Museum, pp. 12-15, and map pl.; compare also Bull. 215-6, N. Y. State Museum, pp. 28, 46, figs. 10, 11; Bull. 154, N. Y. State Museum, pp. 30-3, fig. 5; Bull. Geol. Soc. Amer., vol. 33, p. 525.

¹⁵ Bull. 84, N. Y. State Museum, p. 220.

¹⁶ Bull. 158, N. Y. State Museum, p. 34; Bull. 164, N. Y. State Museum, p. 22; Mon. LIII, U. S. Geol. Survey, pp. 325, 445; Proc. Roch. Acad. Sci., vol. 5, p. 138.

the almost resundered Huron waters during the later Nipissing-Ottawa outlet stage be named "Huronipissing." The temporary lifting of Port Huron to level with or above the Chicago outlet and subsequent abatement witnesses to the migrating bulge hereinbefore advocated.

CORRELATION CHART

The relations of these water bodies as above understood are exhibited in the accompanying correlation chart, in which contemporaneity is horizontally represented and time reads from top downward. Proportional time values are not closely attempted with present inadequate knowledge, but attention is called to the rhythmically spaced ice maxima, which may have a coefficient of approximately 26,000 years. The purpose of the chart is to focus attention on outstanding problems and provoke fresh attack.

A similar chart projected for the minor lakes of western and central New York is deferred to a future writing, but the following pertinent note is retained here:

CATTARAUGUS LAKES

Exploration in the Cattaraugus country during the past summer revealed a fine channel leading from the South Branch Cattaraugus Creek westward toward New Albion, with summit elevation about 1,430 feet above tide. As this is intermediate in altitude between the Lime Lake (Machias) and Persia outlets already recognized by Fairchild,¹⁷ the succession of lakes in the Cattaraugus Valley gains a new member. Another probable outlet examined is the pass north of Ellicottville at about 1,640 feet aneroid (sheet not issued). It would seem that the Dayton pass used by the Buffalo and Jamestown division of the Erie Railway must also have carried some overflow for a time, but there is no good channel across the col.

SOME PREGLACIAL RIVERS

In the nature of a supplementary proposal, the following names are tentatively put forward for certain fairly established rivers of preglacial drainage: "Allegowanda" for the ancient upper Allegany, with discharge by Gowanda to the lower Cattaraugus Valley; "Geneseraga" for the ancient Genesee past Sonyea into the Canaseraga trunk valley and, thence lower, through the Irondequoit trough, and "Senecahanna" for the ancient upper Susquehanna flowing out by the Seneca Lake Valley to the Ontarian River.

¹⁷ Bull. 106, N. Y. State Museum, pp. 16-17, 35.

ORDOVICIAN OVERLAP IN THE PIEDMONT PROVINCE OF PENNSYLVANIA AND MARYLAND¹

BY GEORGE W. STOSE AND ANNA I. JONAS

(Presented before the Society December 29, 1922)

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GENERAL RELATIONS

The presence of Cambrian and early Ordovician sediments on the northwest edge of the Piedmont Province of Pennsylvania and Maryland has long been known, but it has not been heretofore suspected that younger Ordovician strata not only overlap these early Paleozoic sediments, but also extend far southeastward onto the crystalline schists of the Piedmont.

The Piedmont upland of eastern Pennsylvania is traversed by a limestone valley which extends southwestward from Schuylkill River, north of Philadelphia, to Littlestown, near the Maryland State line. From the Schuylkill to Quarryville it is narrow and is called Chester Valley. Beyond Quarryville it expands northward into the wider Lancaster Valley around Lancaster. West of the Susquehanna it again becomes narrow, is known as the York-Hanover Valley, and extends to Littlestown. The valley is underlain by Paleozoic limestones. It is bordered on the northwest in part by the overlapping Triassic sediments and in part by the Cambrian arenaceous sediments of the Pigeon and Hellam Hills and of Mine Ridge and North Valley Hills. It is bordered on the south by overthrust Cambrian and Pre-Cambrian schists. Its southwest termina-

¹ Manuscript received by the Secretary of the Society February 15, 1923

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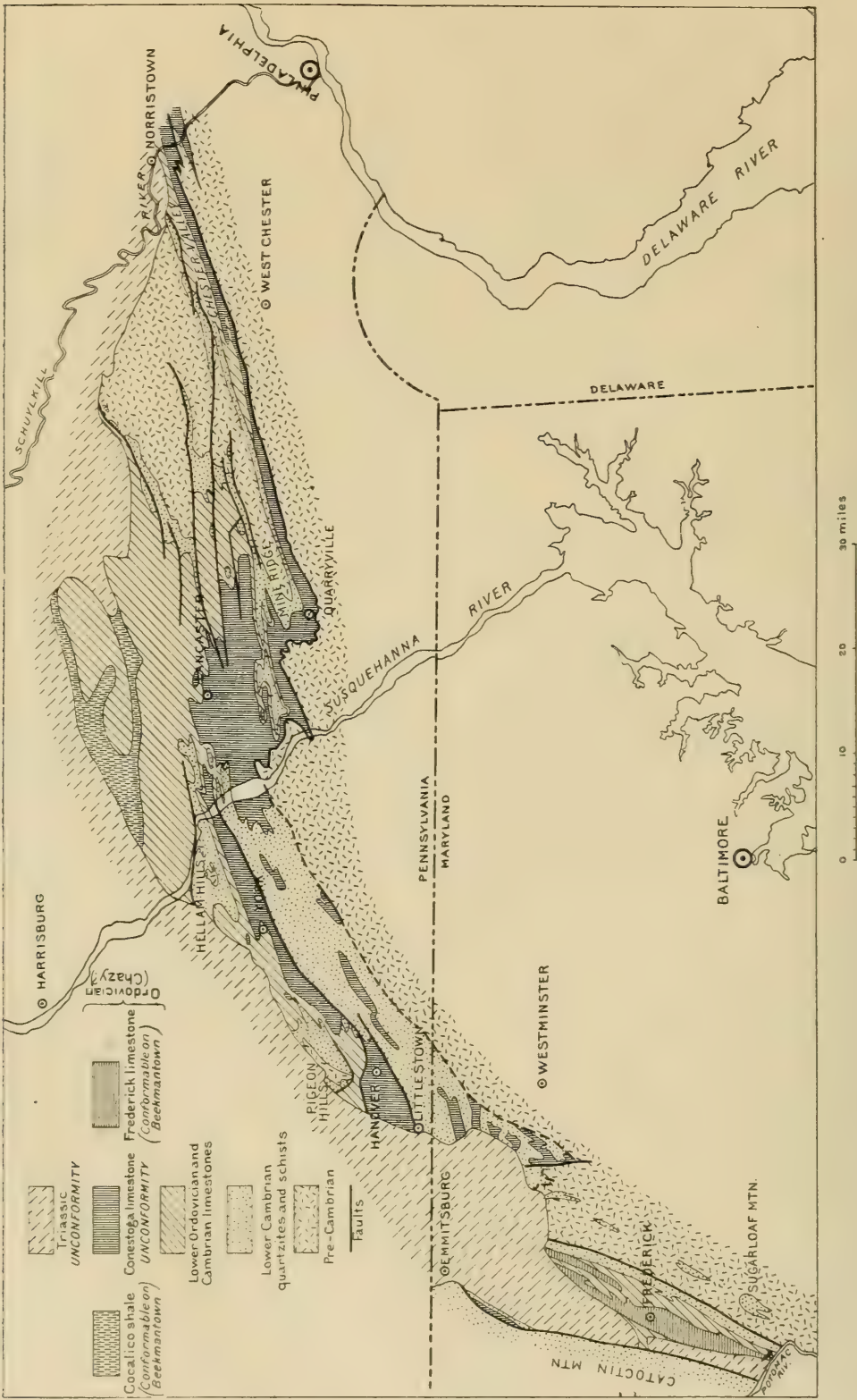


FIGURE 1.—Geologic Map of northwestern Part of the Piedmont Province of Pennsylvania and Maryland
By G. W. Stose and Anna I. Jonas.

tion at Littlestown is due to the overlap of the limestone by the Triassic beds. The Frederick Valley of Maryland is the southwestward continuation of the York-Hanover Valley and is due to the emergence of the limestone from beneath the Triassic cover.

The limestones exposed in the Hanover-York-Lancaster-Chester Valley were until recently treated as a unit by workers in this area and were called the Shenandoah limestone. Detailed study by the writers, especially in the vicinity of Lancaster, has resulted in the distinguishing of seven limestone formations and one shale and the determination of their age and relations. Seven of these formations are found in normal undisturbed sequence northeast of Lancaster, as follows:

Cocalico shale.....	}	Ordovician.
Beekmantown limestone.....		
Conococheague limestone.....		Upper Cambrian.
Elbrook limestone.....		Middle Cambrian.
Ledger dolomite.....	}	Lower Cambrian.
Kinzers formation.....		
Vintage dolomite.....		

These correspond in part with the limestone formations that occur in the Cumberland-Lebanon Valley to the north. The three lower formations are divisions of the Tomstown dolomite of that area, and the uppermost formation, the Cocalico shale, is the equivalent of post-Beekmantown limestones of the Cumberland Valley section.

Walcott, in his study of the limestones of the York-Lancaster Valley,² called attention to coarse limestone conglomerates which he described as intraformational and stated that these conglomerates and all the associated limestones of this part of the valley were probably not younger than Lower Cambrian.

In the detailed study by the present writers it was found that the conglomerates occur at no definite stratigraphic position, but are associated with different beds at different places. They are also generally interbedded with thin-bedded, dark-blue, slaty, argillaceous limestones similar to some in the Kinzers formation, but of much greater thickness. Furthermore, in the southern part of the valley, especially around Lancaster, similar thin-bedded, dark-blue, argillaceous limestones, interbedded with distinctive blue granular limestone beds and dark graphitic slates, predominate. The relation of these beds to formations whose sequence was known led the writers to the conclusion that they belong to an overlapping younger formation at the base of which limestone conglomerates

² C. D. Walcott: U. S. Geol. Survey Bull. 134, 1896, p. 29.

occur in places, but it was not until fossils of probable Chazy age were found in slaty limestone beds interbedded with limestone conglomerate, near York, that the age of the formation was determined. It has now been established that this slaty limestone of probable Chazy age, called the Conestoga limestone, laps progressively southeastward over the formations below the Ledger dolomite down to the Harpers schist, on which it rests in many places in southern Pennsylvania and in Maryland. The extent of the formation from the Schuylkill southwestward into Maryland and its overlapping relation to other formations are shown on the map (figure 1).

DETAILS OF THE CONESTOGA OVERLAP

The Conestoga limestone is restricted, so far as it has been observed at present, to the southeastern part of the limestone valley in the Piedmont. At Lancaster, where it reaches about its northwesternmost position in the valley, it rests on the Ledger dolomite. Its unconformable relation to the dolomite is excellently shown in exposures in quarries and stream banks, just northeast of the city. An old quarry near the Lancaster waterworks, on Conestoga Creek, excellently exposes the sharp unconformable contact of coarse basal conglomerate, containing white marble blocks as much as 5 feet across, on an eroded surface of well-bedded Ledger dolomite (see figures 2 and 3). At the Pennsylvania Railroad bridge over Conestoga Creek at the Lancaster waterworks solution crevices 3 feet wide and 20 feet or more deep, in pure white marble, are filled with limestone breccia containing smaller blocks of similar white marble (see figures 4 and 5). The white marble, apparently a bed in the Ledger dolomite, had been partly eroded prior to the deposition of the Conestoga, and fragments of it were included in the conglomerate that fills the solution crevices in the partly eroded masses of white marble. The conglomerate rests on the floor of Ledger dolomite in adjacent areas where the marble bed had been entirely removed. These limestone conglomerates are interbedded with dark-blue, slaty, argillaceous limestone of Conestoga type, some of which weathers ribbed (see figure 9). The variable character of the sedimentation of the Conestoga is shown in a small quarry near Leaman Place, where thin-bedded siliceous ribbed limestones pass abruptly into thick-bedded granular limestone and lenticular beds of coarser conglomerate (see figures 6 and 7).

Southeast of Lancaster the Conestoga overlaps onto lower and lower beds of the Ledger until, near Leaman Place, it is nearly down on the Kinzers formation. At the Bellemont quarries, 2 miles southeast of

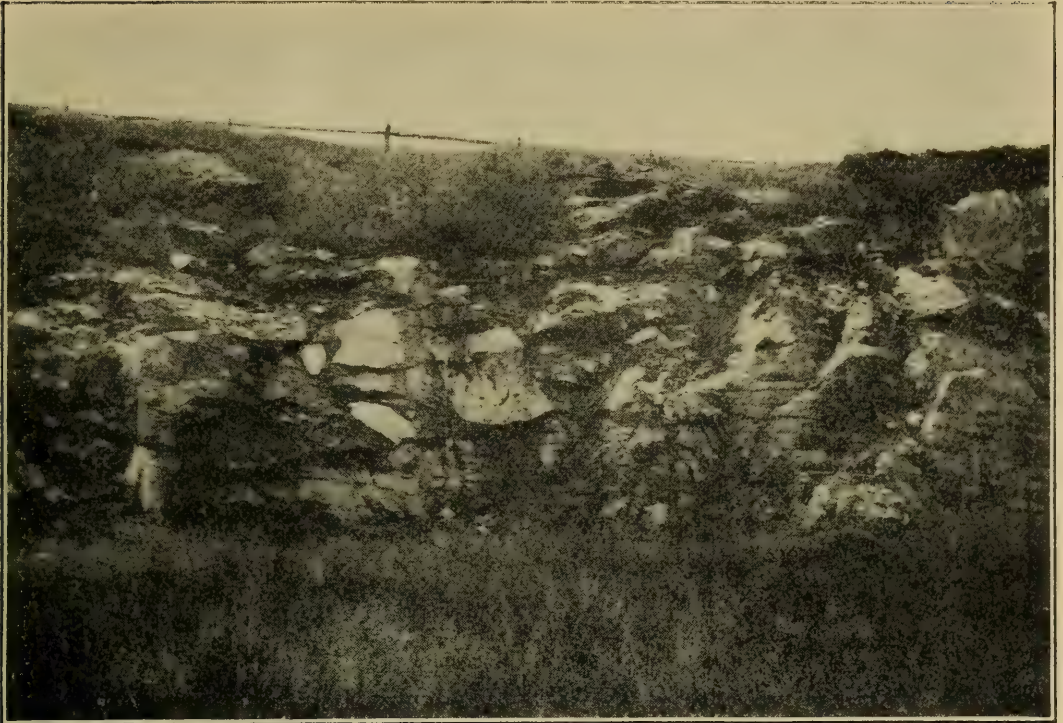


FIGURE 2.—*Limestone Conglomerate at Base of Conestoga Limestone unconformable on Ledger Dolomite*

In old quarry 2 miles northeast of Lancaster.

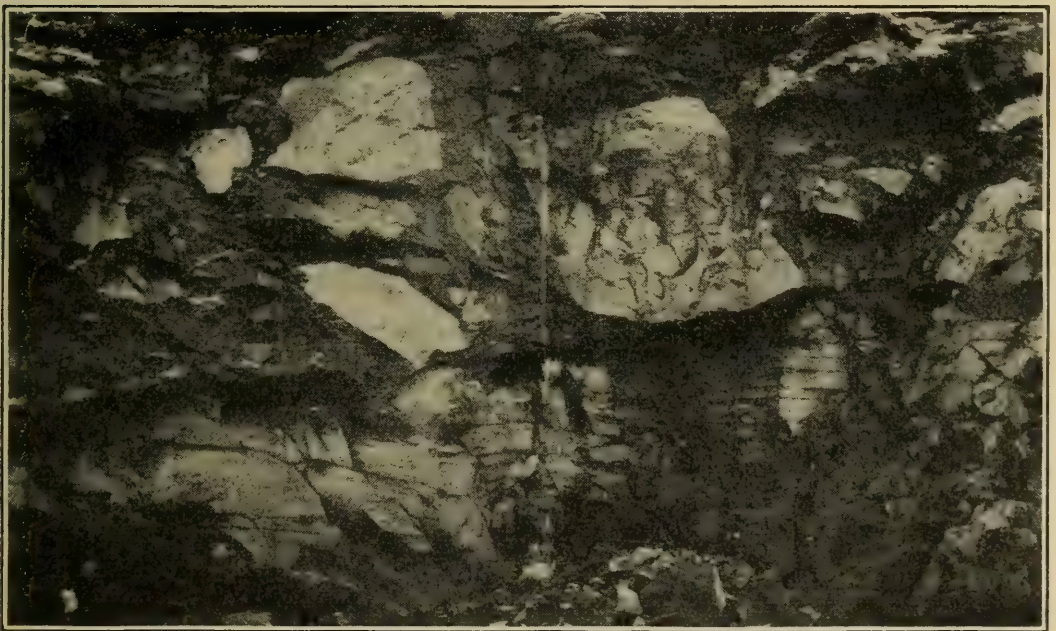


FIGURE 3.—*Unconformable Contact of Limestone Conglomerate containing subangular Blocks of white Marble at Base of Conestoga Limestone on Ledger Dolomite*

Closer view in old quarry 2 miles northeast of Lancaster.

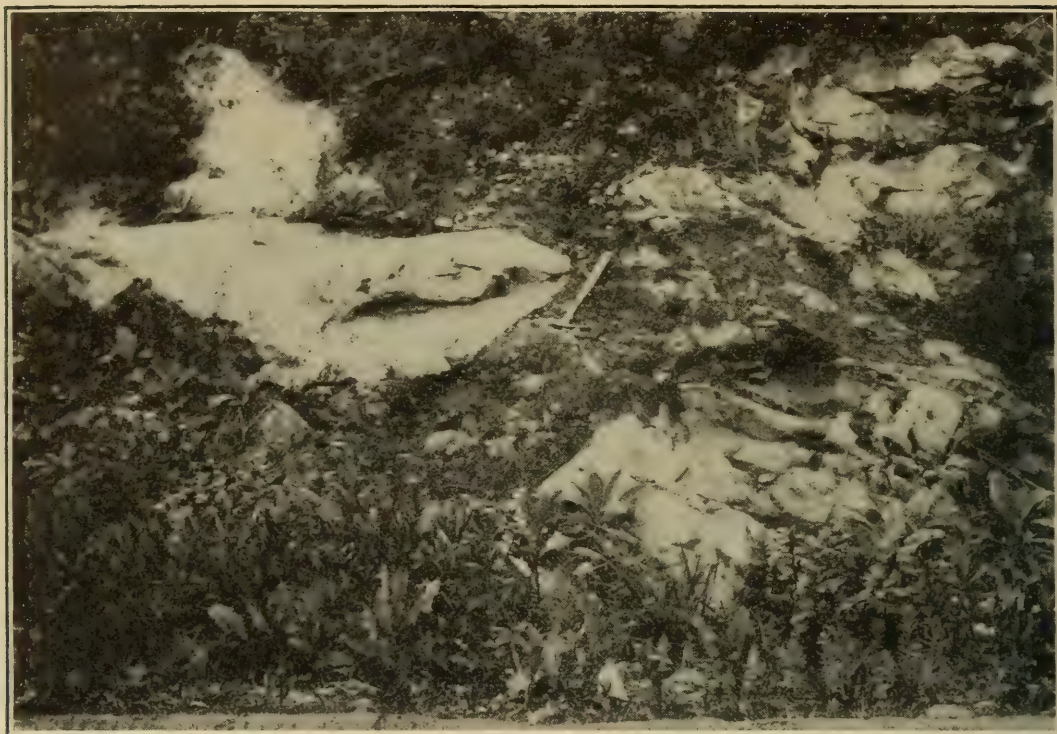


FIGURE 4.—*Solution Crevice in white Marble of the Ledger Dolomite filled with Limestone Breccia at base of Conestoga Limestone*

View taken on the west bank of Conestoga Creek, at Lancaster waterworks.

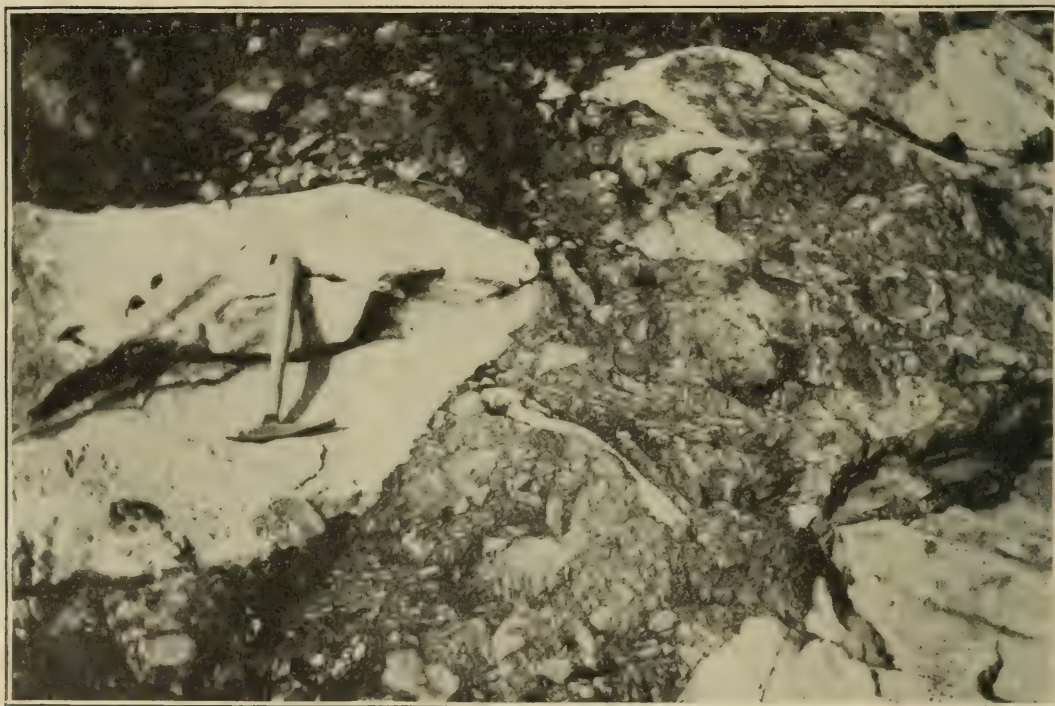


FIGURE 5.—*Closer View of Limestone Breccia at base of the Conestoga Limestone in Solution Crevice in white Marble of Ledger Dolomite*

View taken on the west bank of Conestoga Creek, at Lancaster waterworks.



FIGURE 6.—*Rapid Change in Character of Sediment of the Conestoga Limestone; also Bed of Conglomerate (upper right)*

Wall of quarry a half mile north of Leaman Place.

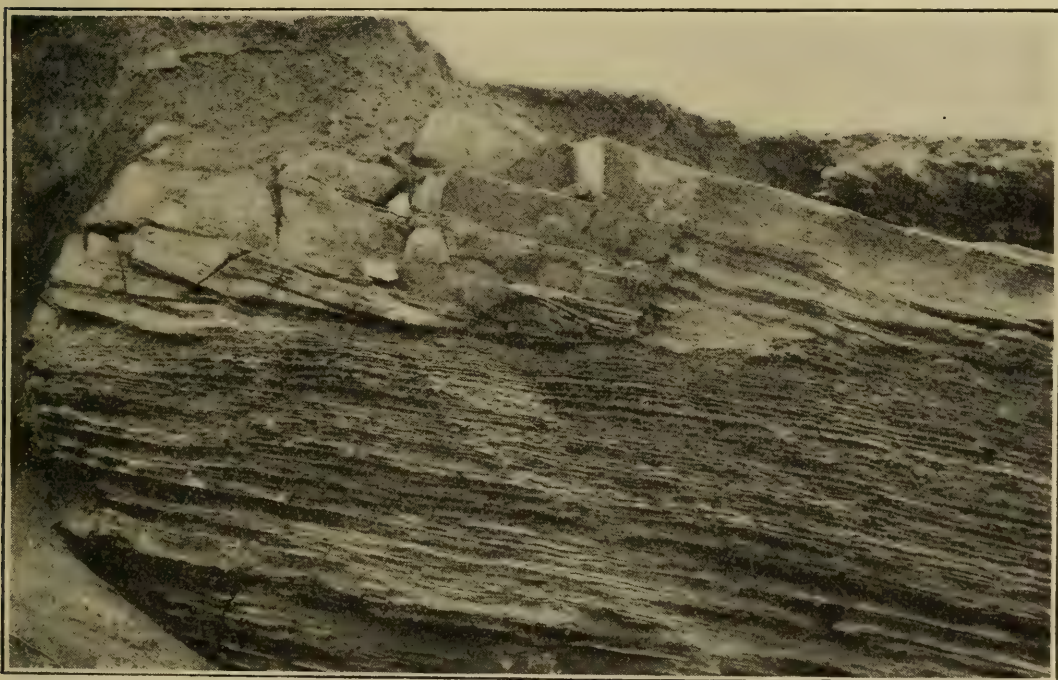


FIGURE 7.—*Thick-bedded granular Dolomite passing into finely laminated impure Ribbed Limestone typical of the Conestoga Limestone*

Closer view of wall of quarry a half mile west of Leaman Place.

Leaman Place, limestone conglomerate and associated slaty limestone of the Conestoga rest on the Vintage dolomite (see figure 8). Although the Kinzers formation is fully exposed in the Pennsylvania Railroad cut just to the north, the Conestoga is nowhere seen resting on the Kinzers. This overlap is apparently concealed by a thrust-fault that passes between these two exposures.

A little farther south, on the north flank of the Mine Ridge anticline, the Conestoga almost completely overlaps the Vintage dolomite, and on the south flank it entirely overlaps the Vintage and rests on Harpers schist. The Conestoga limestone north and east of Quarryville has been recrystallized into compact gray and white banded micaceous marble, which is closely folded and fluted (see figure 10). The local extreme anamorphism is described by E. B. Knopf and A. I. Jonas in a paper on the Quarryville region.³

The Conestoga limestone covers the whole floor of Chester Valley from its southwest end, at Quarryville, nearly to Coatesville. East of Coatesville it is restricted to the southeast side of the valley, and the Cambrian limestone formations appear one by one toward the northeast, progressively emerging from beneath the overlapping Conestoga (see map, figure 12). East of Downingtown the overlapping limestone is locally preserved in a narrow synclinal fold in the middle of the valley where it retransgresses the boundaries of two of the higher formations (see map, figure 13). The Conestoga here is not so greatly metamorphosed and is made up of conglomerates interbedded with argillaceous, somewhat micaceous, limestone and thin graphitic slates. Still farther northeast the Conestoga limestone occupies only a small southern part of Chester Valley, the Cambrian formations occupying the larger northern part. Near the Schuylkill River the Conestoga apparently overlies the Beekmantown limestone, but this area has not been studied in detail by the writers.

West of Lancaster the Conestoga gradually overlaps the Ledger dolomite and rests on the Kinzers formation, and further west on the Vintage dolomite. It forms almost the whole of the limestone valley around Columbia, only a narrow band of the Vintage lying between it and the Cambrian quartzite and schist of the Chestnut Hill anticline on the north and of two anticlines of the Harpers schist on the south. Limestone conglomerates here persist as an integral part of the basal beds of the Conestoga and are finely exposed in the Wrightsville quarries. Certain peculiar blue and black earthy shales and sandy beds that appear near

³ *Am. Jour. Sci.*, 5th ser., vol. 5, January, 1923, pp. 59-61.



FIGURE 8.—*Thick bed of Limestone Conglomerate with underlying thin-bedded dark calcareous Slate of the Conestoga Limestone unconformable on massive Ledger Dolomite*

View of north face of Belmont quarry, 2 miles southeast of Leaman Place. Photograph by C. D. Walcott.



FIGURE 9.—*Thinly laminated impure Limestone characteristic of the Conestoga Limestone*

Exposed in floor of quarry one mile east of Lancaster.

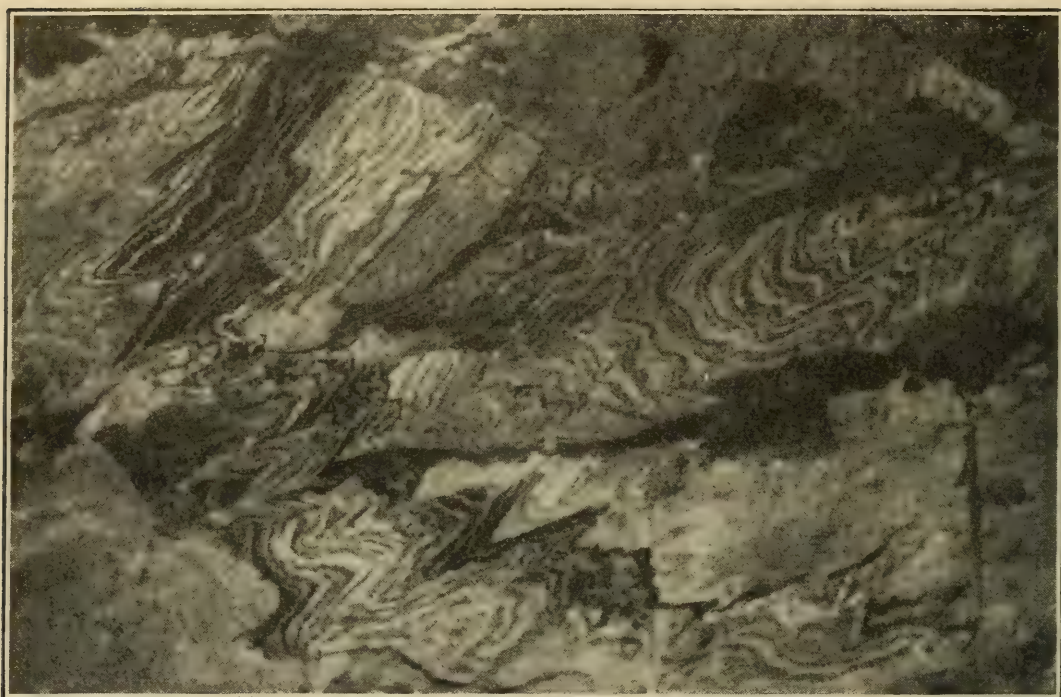


FIGURE 10.—*Closely folded and fluted gray and white banded micaceous Marble of the Conestoga Limestone in a small overturned Syncline*
Face of quarry a half mile northwest of Quarryville.

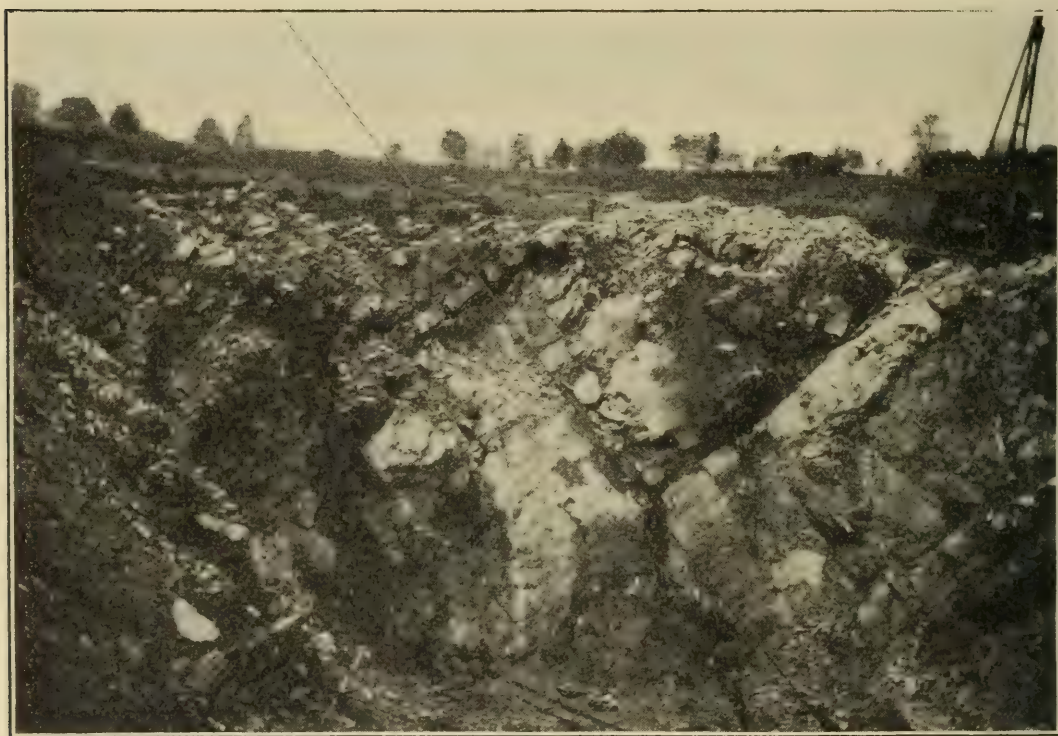


FIGURE 11.—*Fossiliferous Beds in the Conestoga Limestone*

Massive beds of dolomite and limestone conglomerate are overlain at left by dark argillaceous-ribbed fossiliferous limestone. View taken at York Lime & Stone Co.'s quarry, 6 miles east of York.

the base of the formation in the vicinity of Columbia increase in thickness westward and in the vicinity of York give rise to prominent low ridges and hills capped by sandstone.

Southwest of York the overlap relation, which in itself is complicated, is further confused by thrust-faulting. The Conestoga limestone is largely restricted to the southeast side of the valley, but some outliers of the basal sandstones and conglomerates of the formation cap hills near the north border of the valley. Several excellent exposures of the contact of the basal beds of the Conestoga on the Ledger dolomite were seen in the Pennsylvania Railroad cuts northeast of Spring Grove, where folding has brought the underlying dolomite to the surface. Here conglomerates of white marble fragments inclosed in a matrix of siliceous argillaceous limestone occur near the base, and slaty limestone beds fill hollows in the underlying Ledger dolomite. A narrow crevice in the dolomite, filled to a depth of about 15 feet with limestone breccia and masses of oolitic limestone, is laid bare in the railroad cut. In the vicinity of Hanover the Conestoga spreads out over the larger part of the valley and is faulted and overthrust on the Cambrian limestones. Southwest of Hanover the Triassic sediments transgress southward, first covering the Cambrian limestones and then the Conestoga limestone, so that beyond Littlestown the limestones are entirely concealed and the York-Hanover limestone valley ends.

South and southeast of the York-Hanover Valley there are narrow belts of blue slaty limestone in the Harpers schist which are regarded as infolds of overlapping Conestoga limestone. During a recent survey of Carroll County, Maryland, the junior author has found similar blue limestone along a belt of valleys extending from the State line south of Littlestown to and beyond Union Bridge, Frederick County, Maryland. This blue slaty limestone is believed to be a southern occurrence of the Conestoga formation that overlaps the Harpers schist and is infolded in synclines in the schist. The Conestoga limestone and Harpers schist are similarly associated in a small elongated area southwest of Emmitsburg, in Frederick County, Maryland, where these rocks are locally exposed west of the Triassic belt.

In Frederick County, Maryland, limestones again emerge from beneath the cover of Triassic sediments and form the Frederick Valley. The Conestoga limestone is not known to be present in this valley, but a somewhat similar limestone, called the Frederick limestone, overlies the Beekmantown limestone, apparently conformably. It contains a small fauna, some forms of which are the same as those in the Conestoga, and the two limestones are probably in part of the same age.

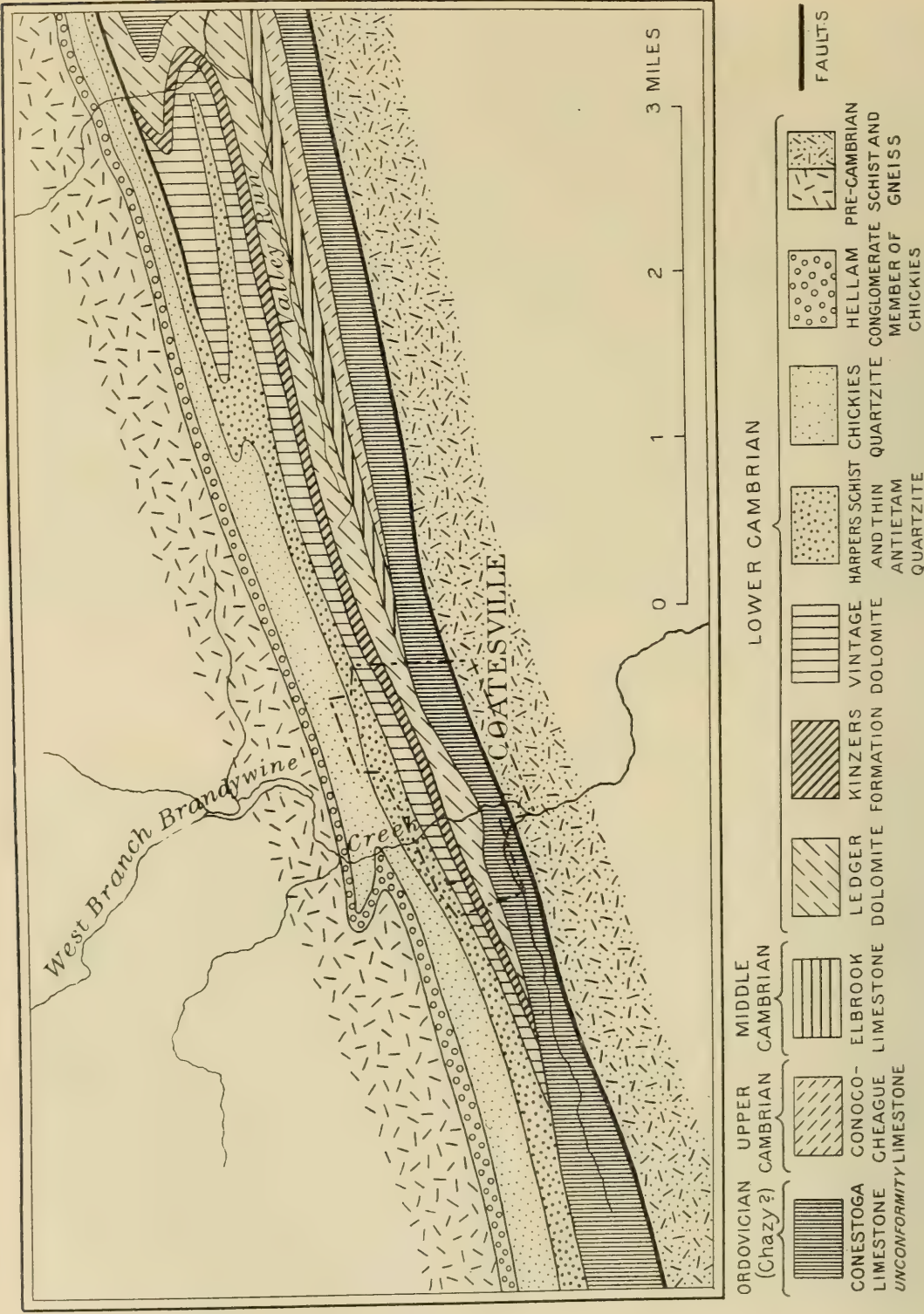


FIGURE 12.—Geologic Map of Chester Valley in the vicinity of Coatesville
Showing the gradual overlap of Conestoga limestone westward over the older limestones.

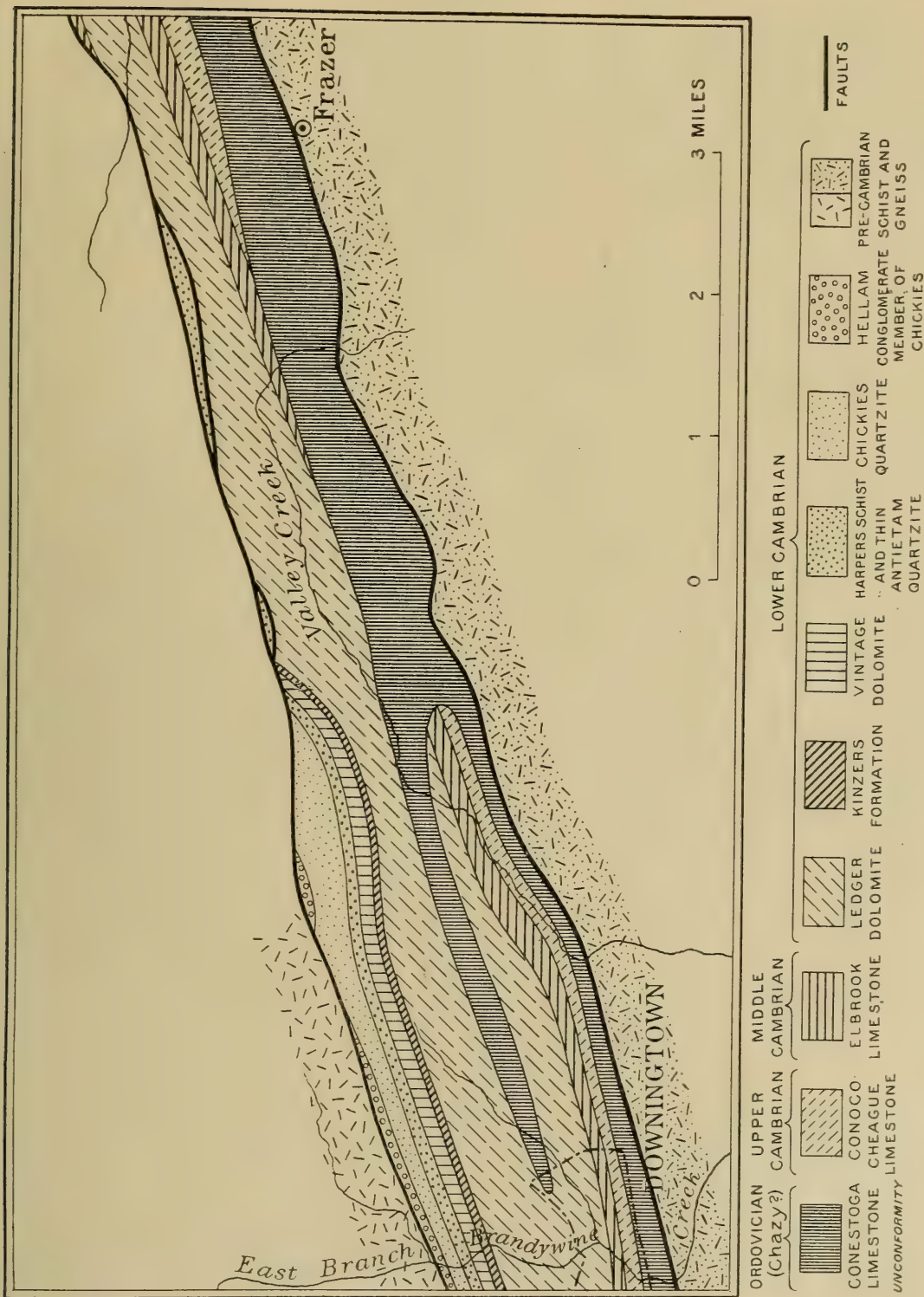


FIGURE 13.—Geologic Map of Chester Valley in the vicinity of Downingtown
Showing the Conestoga limestone in a synclinal fold overlapping the older limestones.

FOSSILS AND CORRELATION

Before fossils were found in the Conestoga limestone its overlapping relation to the underlying formations had been observed and worked out in the vicinity of Lancaster. The Conestoga was known to be younger than the Ledger dolomite, on which it rests, with a marked unconformity near Lancaster. Within 5 miles northeast of Lancaster, the Ledger dolomite is overlain by the Elbrook, Conococheague, and Beekmantown limestones, in normal sequence. As none of these formations in any way resemble the Conestoga in lithology, it is reasonable to assume that the Conestoga is younger than they are—that is, post-Beekmantown. The first fossils found in the limestone were small segments of crinoid stems collected in the vicinity of York, and they determined the age of the rocks to be not older than Ordovician. Later, brachiopods and crinoid plates were collected from slaty impure limestones interbedded with thick conglomerate beds at the York Lime & Stone Co.'s quarry 6 miles northeast of York (see figure 11). The only species of shell that is determinable is *Strophomena stosei*, a form not previously known elsewhere except in the Frederick limestone of Maryland, which has been described by Bassler.⁴ The crinoid plates are not determinable, but are apparently of Ordovician types. The Frederick limestone has yielded, besides *Strophomena stosei*, other shells and trilobites identified by Bassler as *Acidaspis ulrichi*, *Triarthrus* sp., and undetermined species of *Reteocrinus*?, *Cameroceras*, and *Isotelus*. These forms are not known to occur in any other formation, but are regarded by Bassler as probably Chazy.

Near Oregon, 7 miles northeast of Lancaster, the Beekmantown is overlain by the Cocalico shale in which graptolites of Normanskill type have been found and which is therefore also probably of Chazy age. Similar shales of Chazy age have been discovered in the Lebanon Valley, where Normanskill graptolites were collected by the senior author near Highspire, southeast of Harrisburg, and the shale belt was traced eastward as far as Reading. The shales outcrop on opposite sides of the Triassic basin and probably are parts of a shale mass that underlies the cover of Triassic sediments.

The Conestoga limestone is characteristically a dark-blue crystalline limestone and dark argillaceous limestone with graphitic slate partings and shale beds, some of which are of considerable thickness. Even the pure marble conglomerate beds at the base are interbedded with slate and

⁴ R. S. Bassler: The Cambrian and Ordovician deposits of Maryland. Maryland Geol. Survey, Cambrian and Ordovician, 1919, p. 117.

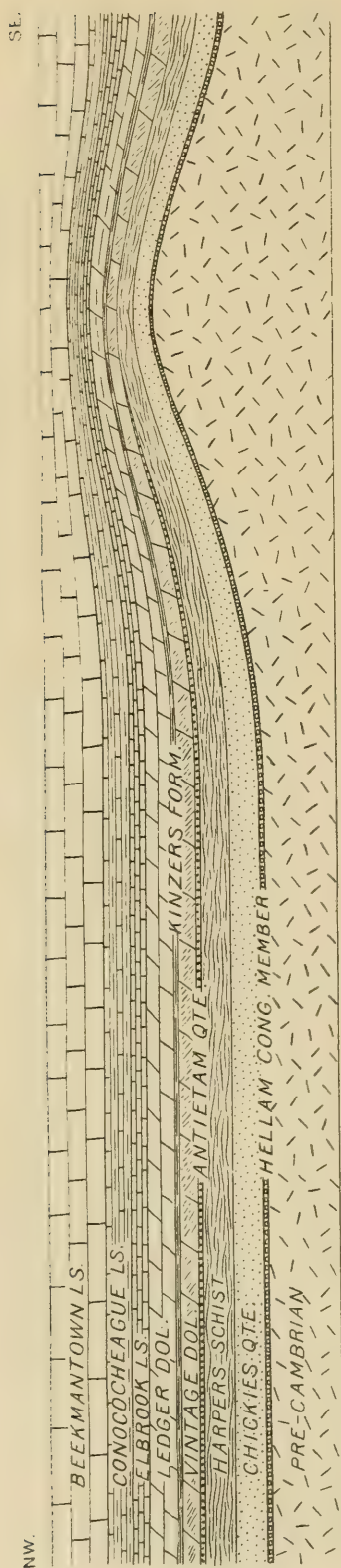
hard slaty ribbed limestones (see figures 6 to 9). These impurities are chiefly argillaceous matter similar to that which forms the Cocalico shale. It is believed, therefore, that the Cocalico shale and Conestoga limestone are approximately of the same age and were deposited in the same sea, the argillaceous matter predominating where the Cocalico shale was deposited, and a mixture of lime silt and argillaceous mud being deposited in the area of Conestoga limestone.

SUMMARY

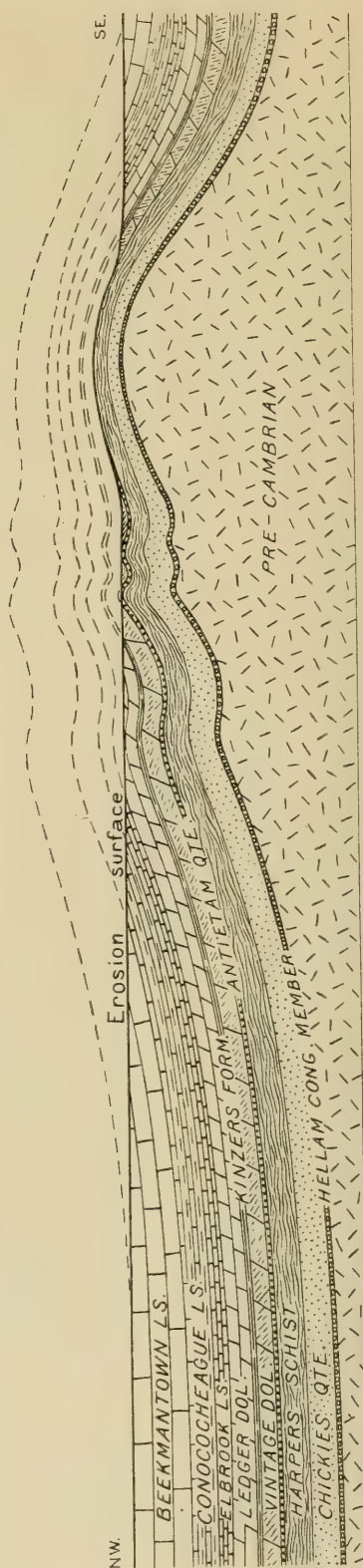
The history of Cambrian sedimentation and deformation and the Conestoga overlap in early Ordovician time may be summed up as follows:

During early Cambrian time a shallow arm of the sea occupied the western part of the Piedmont area of Maryland and Pennsylvania and the adjacent part of the Appalachian trough, in which sediments were deposited. First, sandy and argillaceous detrital material, eroded from an uplifted land area farther southeast in the Piedmont Province, was washed into the sea and deposited, forming the siliceous Lower Cambrian sediments. This deposition was followed by a period in which the elevation of the Piedmont land area was insufficient to cause large quantities of detrital material to be washed into the sea, and lime silt was deposited. Small amounts of siliceous and argillaceous silt were included as impurities in some of the beds, giving rise to shaly and impure limestone beds which occur chiefly in the Kinzers, Elbrook, and Conococheague formations. Lime silt was deposited apparently continuously throughout the rest of Cambrian time and the early part of Ordovician time, although there may have been epochs when deposition ceased and the sea-bottom may even have been temporarily raised above sealevel. Such breaks in sedimentation were most likely to have occurred along the axis of the Mine Ridge uplift, for the sediments observable on its flanks are somewhat thinner than those in the trough to the northwest, but the beds that were originally on its crest are now entirely eroded so that their former extent can not be determined. The formations in Chester Valley, southeast of the axis of uplift, are also thinner than those in the Lancaster Valley. In the diagrammatic section (figure 14), which shows the writers' conclusions as to the deposition of sediments in the area, the deposits are represented as thinner over the rising axis.

At the end of Beekmantown sedimentation further uplift along the Mine Ridge axis brought the newly deposited sediments above sealevel and subjected them to erosion. All the softer lime-silt formations, which

FIGURE 14.—*Early Sedimentation*

The deposition of the Lower, Middle, and Upper Ordovician formations is shown as continuous in the Lancaster Valley, in the Chester Valley, and over the rising Mine Ridge anticline, but the sediments are represented as thinner on the axis of uplift.

FIGURE 15.—*Early Ordovician Uplift and Erosion*

The sedimentary formations were raised above sealevel by the bowing up of the Mine Ridge anticline after the deposition of early Ordovician (Beekmantown) strata, and the softer formations were eroded from this arch.

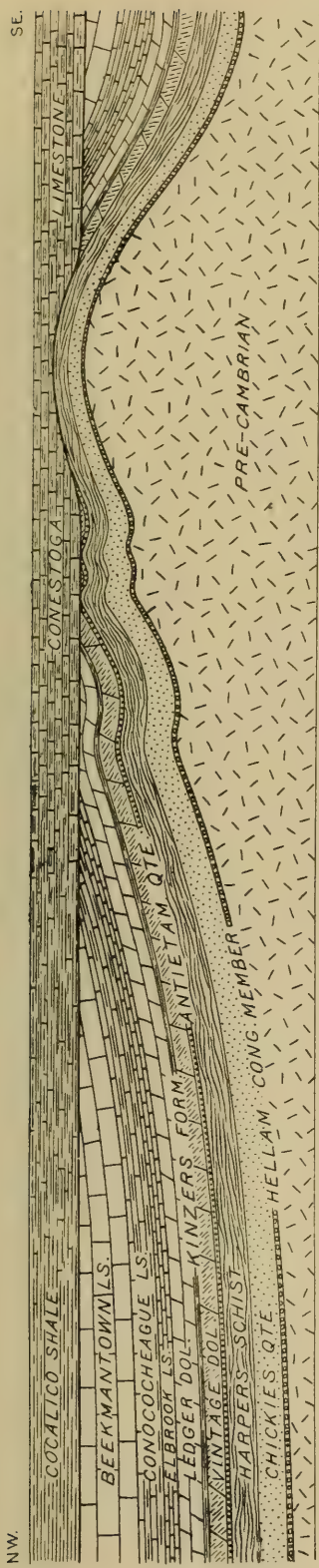


FIGURE 16.—*Later Ordovician Sedimentation and Overlap*

The retransgression of the sea, later in Ordovician (probably Chazy) time, deposited shales and shaly argillaceous limestones of the Cocalico and Conestoga formations, which overlap all older formations on the flanks of the Mine Ridge anticline down to the Harpers schist, and are believed to be approximately of the same age.

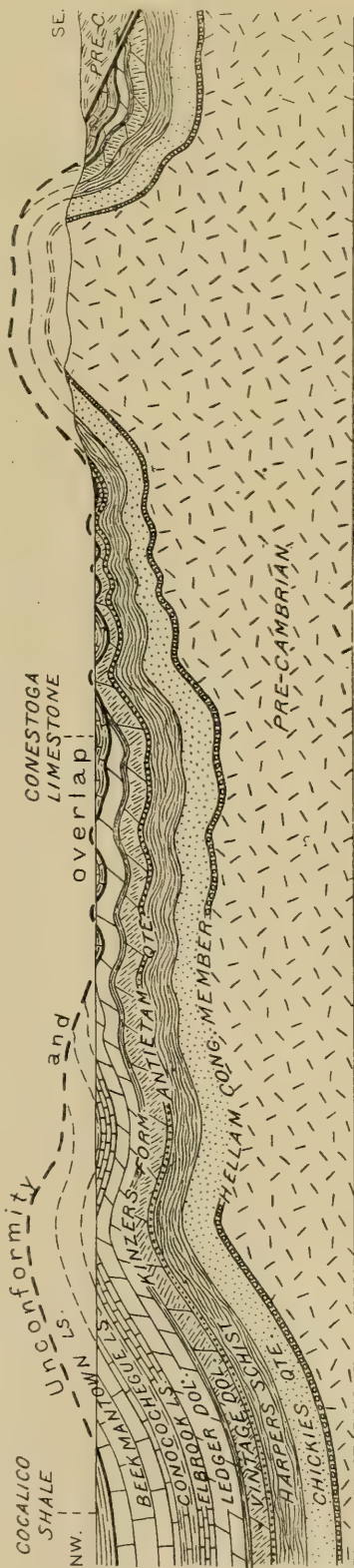


FIGURE 17.—*Later Folding, Uplift, and Erosion*

The overlapping Conestoga limestone and the underlying formations were closely folded and thrust-faulted and uplifted in late Paleozoic time and were subsequently reduced to their present form by erosion.

had been more or less consolidated into limestone by pressure, were eroded on the flanks of the uplift and the older and harder siliceous sediments were laid bare and also partly eroded. The beveled edges of the limestone formations thus appeared one after another on the flanks of the bowed-up siliceous sediments, as shown in the diagrammatic section, figure 15. The reinvasion of the sea later in Ordovician time, probably in the Chazy epoch, spread a mantle of sediment unconformably over the beveled edges of the older formations, as shown in figure 16. Fragments of limestone from the waste of the eroded underlying or adjacent formations were included in the initial sediments, giving rise to thick limestone conglomerates. Fine black argillaceous silt that was carried into this sea was apparently not washed from the Piedmont land area to the southeast, but was probably brought from some more distant source at the head of the bay to the northeast. This argillaceous silt formed the Cocalico shale in the open part of the basin, where currents supplied it freely, and at approximately the same time it probably contributed the argillaceous matter to the impure slaty Conestoga limestone on the southeast side of the basin, where the water was shallower owing to the Mine Ridge uplift, and the currents were thus deflected or retarded, so that a larger proportion of lime silt was there deposited. Later, the further upbowing of the Mine Ridge anticline and of minor anticlines on its flanks, accompanied by thrust-faulting, resulted in the emergence of the land above the sea and the erosion of the folded strata, as shown in figure 17, which presents conditions as they are today.

APPALACHIAN BAUXITE DEPOSITS ¹

BY WILBUR A. NELSON

(Read before the Society December 30, 1922)

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INTRODUCTION

In a paper given at the 1921 annual meeting of the Geological Society of America, entitled "A volcanic ash-bed in the Ordovician of Tennessee, Kentucky, and Alabama," the following statement was made in regard to a new theory of the formation of bauxite deposits:

"Experiments made on bentonite show that when boiled with five times normal solution of sulphuric acid for five hours the colloidal properties are destroyed; that about 85 per cent of the aluminum oxide goes into solution as aluminum sulphate, along with the alkalies present, but that all the silica except a trace remained undissolved. This fact offers a possible solution to the origin of bauxite, as laboratory experiments show that such a solution of aluminum sulphate is precipitated by a solution of tannic acid after standing for a few days. Deposits of bentonite occurring in contact with pyritiferous rocks would readily have part of their aluminum contents dissolved out by the sulphuric acid in the ground-water, and such a solution of aluminum sulphate, it seems, would be precipitated by natural reducing agents, such as tannic acid or acid peat-forming bacteria, and thus form certain of our present bauxite deposits."

Following these experiments, it was decided to visit the Chattanooga bauxite deposits and make a detailed study of the geology of the Mission-

¹ Manuscript received by the Secretary of the Society January 29, 1923.

ary Ridge section, lying just east of the city, to see if the bed of altered volcanic ash, the bentonite, which should occur in the Ordovician rocks on the west side of Missionary Ridge, was present.

The area in East Chattanooga lying at the west foot of the ridge and directly to the west of the large bauxite mines of the Kalbfleisch Chemical Corporation was visited and a fine exposure of the bentonite found at the top of Bragg's quarry, located at the intersection of Bragg Street with the Southern Railway, and later a good exposure was found in the yard of the Avondale school, about five-twelfths of a mile farther south. Two-thirds of a mile east of these outcrops occur the bauxite mines of Missionary Ridge.

PHYSIOGRAPHY

In the Chattanooga area there are a number of well defined peneplains, and it is thought that one of these played an important part in the formation of the bauxite. They present a most striking aspect when viewed from Lookout Mountain, the top of which is the highest of these old plains. It was called the Cumberland tableland by Safford.² This peneplain has been considered as of Carboniferous age by Hayes.³ Going to the east, we find as the next lowest level the top of White Oak Mountain, with an elevation of from 1,300 to 1,500 feet. From White Oak Mountain on the east, to Waldens Ridge on the west, is a distance from 12 to 18 miles, and in this intervening area are located a number of low-lying ridges of different elevations and the main valley of the Tennessee River. A study of the region shows that Missionary Ridge, with an elevation of 1,000 feet above sealevel, may represent the remnant of another peneplain, and that a series of parallel ridges whose crests are all of approximately the same elevation (850 feet), and which lie between Missionary Ridge and the White Oak Mountain, is the most recent peneplain of this section, with the exception of the present plain of the Tennessee River, with an elevation at Chattanooga of 670 feet.

It is the old peneplain, now lying at an elevation of approximately 850 feet, which particularly interests us in our study of the origin of the bauxite deposits, for the bauxite occurring on the east side of Missionary Ridge is found at this elevation. At that geologic time the present topography would indicate there existed between Missionary Ridge, on the west, and White Oak Mountain, on the east, a broad, flat, featureless plain, 8 to 10 miles wide, with swamps occurring along the eastern base of what is now Missionary Ridge. Bordering the banks of a mighty river then

² J. M. Safford: *Geology of Tennessee*, 1869, p. 10.

³ C. W. Hayes: *Sixteenth Annual Report, U. S. Geol. Survey*, part iii, 1895, p. 592.

meandering in its sluggish course across this ancient land (the forerunner of the present Tennessee) were large marshy, swamp areas covered with dense plant growth. In this area, along the eastern base of this ridge, occurred many springs, bringing up large quantities of water charged with mineral salts, which quickly precipitated on coming in contact with the acid swamp waters and bacterial life of this old geologic plain.

Watson⁴ states that "the formation of this plain was probably during Eocene time. . . . In this event they [the bauxite deposits] must have been formed near the close of the period of the Eocene baseleveling."

The peneplain of which the top of White Oak Mountain is a remnant is capped by Mississippian rock and very probably is an isolated eastern remnant of the Highland Rim peneplain of Middle Tennessee, which on the western side of Middle Tennessee is covered by upper Cretaceous gravel of the Tuscaloosa formation.

Along the western edge of the White Oak Mountain-Highland Rim peneplain are a number of well defined terraces along the Tennessee River. The terraces have been described by Wade,⁵ who distinguishes six distinct terraces below the top of the White Oak Mountain-Highland Rim peneplain, occurring at approximately 780-800 feet, 620-700 feet, 600 feet, 500 feet, 420 feet, and 380 feet, the last being about 10 feet above the floodplain of the present Tennessee River, and considers the upper two terraces, occurring at 780-800 and at 620-700 feet, to be of Pliocene age, while the terraces occurring at 600 feet and lower he regards as of Pleistocene age. These terraces should tie into peneplains formed during those periods, and it is considered that the peneplain on which the bauxite deposits at Chattanooga were formed, and which occurs approximately 450 feet below the top of the White Oak Mountain-Highland Rim peneplain at East Chattanooga, corresponds in age to the river terrace occurring at 600 feet elevation, mentioned above by Wade as having been formed at the beginning of the Pleistocene period. This terrace occurs approximately 450 feet below the White Oak Mountain-Highland Rim peneplain.

In this connection it is interesting to compare the table of terraces of the Pleistocene and upper Pliocene periods, prepared by Osborn and Reeds,⁶ with the above conclusions. Their highest river terraces, stated

⁴Thos. L. Watson: Georgia Geological Survey, Bull. 11, 1904, p. 130.

⁵Bruce Wade: Gravels of West Tennessee Valley. Tennessee Geol. Survey, Rec. of Tennessee, vol. 7, 1917, pp. 55-90.

⁶H. F. Osborn and C. A. Reeds: Old and new standards of Pleistocene division in relation to the prehistory of man in Europe. Bull. Geol. Soc. Am., vol. 33, no. 3, 1922, fig. 13, pp. 411-490.

to have been formed at the beginning of the Pleistocene period, are shown to occur at 90 to 100 meters above existing beds of large rivers, which checks in roughly with the 600-foot Tennessee River terrace discussed above, as it occurs approximately 260 feet above the Tennessee River. Osborn and Reeds consider this to have been the period of Nebraskan glaciation.

It is considered that the bauxite deposits of the Chattanooga district were formed at a much later date than the Eocene, and that one is justified on the basis of the above correlation of tentatively placing their age as of early Pleistocene. Following the close of this baseleveling period came an upward warping of the earth's crust, and this Highland Rim-White Oak Mountain peneplain was uplifted and tilted upward toward the east, so that at the foot of the Cumberland Plateau this peneplain has only an elevation of 1,000 feet as against the elevation of 1,300 feet of the White Oak Mountain, or a progressive uplift toward the east of 300 feet. This upward movement, which probably started gradually during the Pliocene or at the beginning of Pleistocene time, with a tilting upward of the rocks to the east, naturally caused a migration of the streams flowing on this old peneplain to the western side of whatever valleys they occupied, and in this particular valley between Missionary Ridge and White Oak Mountain caused a shifting of the stream up close to the eastern base of Missionary Ridge and the location of river swamp areas in this particular region.

A study of the Kalbfleisch bauxite mines in this region shows lying to the west of the bauxite deposits and contiguous to it a deposit of dark brown lignite and lignitic clay, which was measured where exposed as being 36 feet long and having a maximum thickness of 25 feet. The presence of this lignite deposit in connection with the bauxite ore shows very clearly that this ore was formed on an old peneplain which now has an approximate elevation of 850 feet, and that the bauxite was formed in an area where swamp conditions existed suitable for peat formation and deposition and where the surface waters were of the acid swamp-water type, full of tannic and humic acids.

GEOLOGY

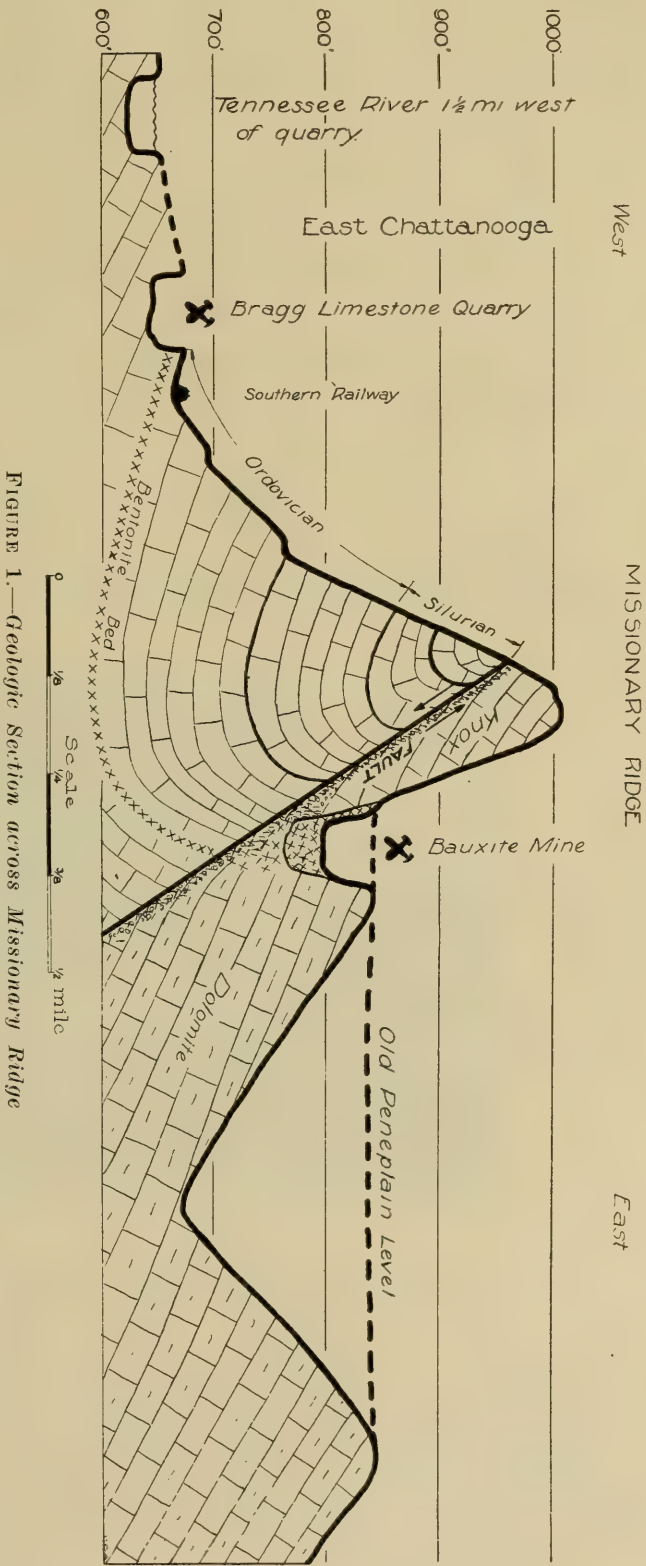
Starting at Bragg's quarry, in East Chattanooga, and going up the west side of Missionary Ridge, one finds an excellent section, beginning at the base of the Lowville formation of the Black River group, of Ordovician age (in which the bentonite occurs), and extending up into the red shales and limestones of the Rockwood formation, of Silurian age,

which are here overlain by cherty Knox dolomite thrust over the Silurian from the east and forming the cap of Missionary Ridge.

STRUCTURE

The strata of the Chattanooga - Missionary Ridge area have been faulted and folded in a manner similar to that of the Appalachian region, and such folding and faulting has been given the name of Appalachian structure.

A cross-section of the geology, as it occurs on a line extending in a roughly west-east direction from Bragg's quarry, in East Chattanooga, across the crest of Missionary Ridge and on toward the White Oak Mountain, shows the Lowville formation containing the 40-inch layer of bentonite, dipping slightly to the southeast under Missionary Ridge. A study of this section shows that the rocks have varying dips of from 2 to 30 degrees, all to the southeast, and that the strata dip under the west side of the ridge. The strata quickly turn upward as they near the line of the thrust-fault and form a closely compressed synclinal fold overturned toward the west.



One of the major thrust-faults of the region, having a low angle of thrust to the northwest and having its strike in a north 30 degrees east course along the west side of the crest of Missionary Ridge, has thrust over the closely compressed fold, of Silurian and Ordovician rocks, the cherty Knox dolomite of Canadian and Ozarkian ages.

The bauxite deposits occur on the east side of Missionary Ridge, a short distance below the crest, at a point where the line of the thrust-fault is still very near to the surface.

At this point, which was at the time of formation of the bauxite an old peneplain, the ground-water circulating upward along this fault readily came to the surface through the few feet of fractured chert and dolomite lying between the fault-plane and the ancient land surface on which these underground waters came forth.

BENTONITE AND BAUXITE

The bentonite layer outcropping at the top of Bragg's quarry dips underground to the eastward and, as is shown by the accompanying cross-



FIGURE 2.—*Bed of Bentonite*

The bed outcrops at the top of the Bragg limestone quarry, East Chattanooga, Tennessee. Photograph by Wilbur A. Nelson.

section, quickly turns upward and is cut off by the thrust-fault just above which is now found the bauxite deposits.

The bentonite outcropping just five-eighths of a mile to the west of the Kalbfleisch bauxite mines measures 40 inches in thickness. It rests on the massive pure limestone of the Lowville formation and is overlain

in the quarry by 2 feet of yellow, earthy, mud-cracked limestone. An analysis⁷ of the bentonite is as follows:

Complete Analysis of Bentonite, Bragg's Quarry, East Chattanooga

	Per cent
SiO ₂	51.88
Al ₂ O ₃	19.13
Total Fe as Fe ₂ O ₃	3.03
CaO	4.54
MgO	4.86
K ₂ O	1.56
Na ₂ O	1.94
TiO ₂	.48
Cr	.005
CO ₂	2.94
H ₂ O expelled at 100-110 degrees centigrade.....	3.56
H ₂ O expelled at 150-160 degrees centigrade.....	.72
H ₂ O expelled at 200-210 degrees centigrade.....	.30
HO expelled at red heat.....	5.24

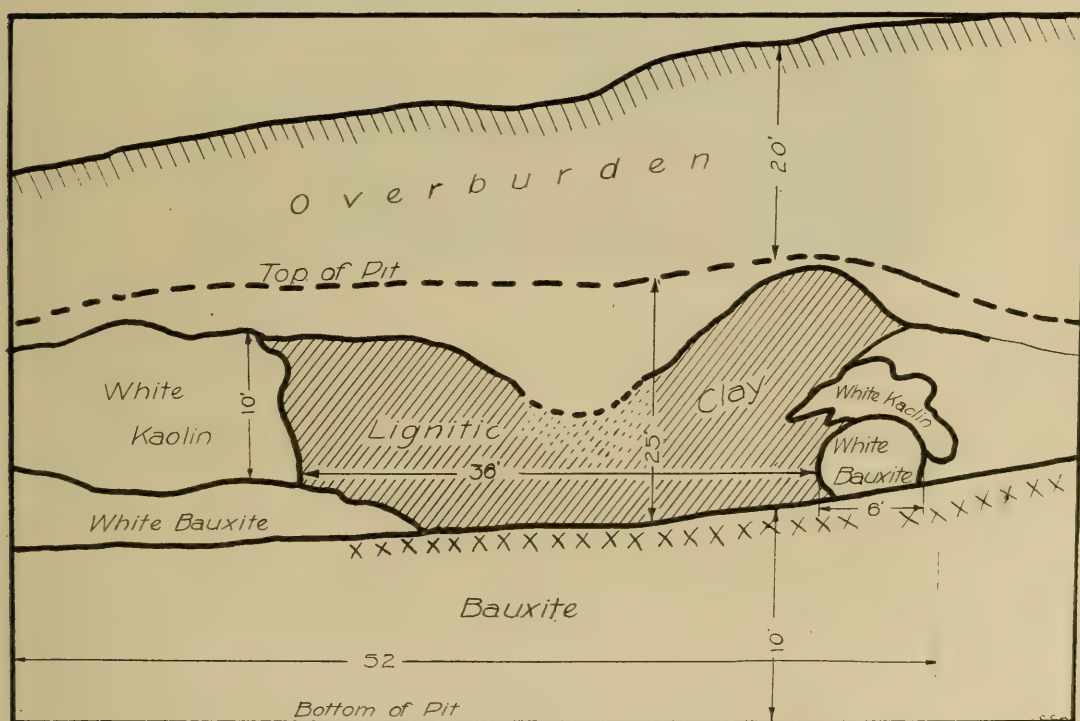


FIGURE 3.—Diagrammatic Sketch of west Side of Isabella Stewart Bauxite Mine

A detailed description of the Isabella Stewart mine of the Kalbfleisch Chemical Corporation, lying five-eighths of a mile west of the bentonite

⁷ All analyses on this and succeeding pages were made by D. F. Farrar, chemist, Tennessee Geological Survey.

outcrop just described, is of interest, for in this mine are found massive and pisolitic bauxite, white, plastic kaolin, lignite, and white, fine-grained, siliceous material which might be considered as tripoli.

The bottom of the pit is in massive fine-grained bauxite, and the walls for 10 feet up are of this same high grade 60 per cent bauxite. Above this, on the northwest side of the pit (the side next to Missionary Ridge), occurs, on the north edge, white, plastic kaolin, and on the south corner of this side of the pit there also occurs white, plastic kaolin: but between these two pockets of kaolin, which are 46 feet apart, lies a mass of black lignitic clay and low-grade lignite. This lignite lies between and extends

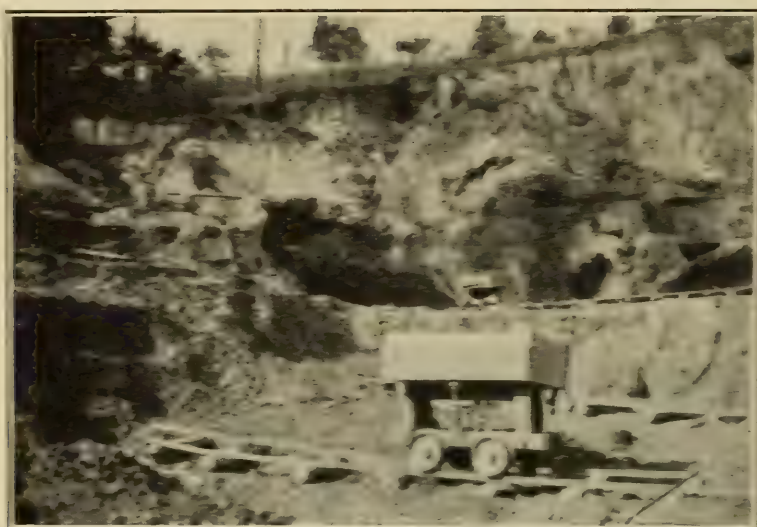


FIGURE 4.—West Side of the present Isabella Stewart Bauxite Mine.

The mine is on the east side of Missionary Ridge, East Chattanooga, Tennessee, and is owned by the Kalbfleisch Chemical Corporation. Photograph by Wilbur A. Nelson.

over the kaolin pockets, which pockets are roughly about 10 feet in height and 6 to 8 feet wide. The maximum thickness of the lignite and lignitic clay is approximately 25 feet. Its top is covered by loose clay full of angular chert debris, typical hillside wash of Missionary Ridge.

On the northeast side of this pit occurs a large mass of fine-grained siliceous material, mentioned above, separating the present workings from the original pits of this mine, which were worked in 1911.

The photograph on page 530, taken of the northwest side of the mine pit, shows the relations of the different beds described above.

ANALYSES

The following analyses were made of the bauxite, kaolin, lignite, and siliceous material.

ANALYSES OF BAUXITE

Hard Ore, National Method

	Per cent
Insoluble	9.17
Al ₂ O ₃	59.47
Fe ₂ O ₃	1.05
TiO ₂	.68
H ₂ O	29.80

Complete Analysis

	Per cent
SiO ₂	5.98
Al ₂ O ₃	60.08
Fe ₂ O ₃	1.12
TiO ₂	3.02
H ₂ O	29.80

Soft Ore, National Method

	Per cent
Insoluble	5.49
Alumina (Al ₂ O ₃)	60.00
Iron oxide (Fe ₂ O ₃).....	1.04
Titanium dioxide (TiO ₂).....	.56
Water	32.68

Complete Analysis

	Per cent
Silica (SiO ₂)	2.40
Alumina (Al ₂ O ₃)	60.46
Iron oxide (Fe ₂ O ₃).....	1.12
Titanium dioxide (TiO ₂).....	3.52
Water	32.68

ANALYSIS OF KAOLIN

National Method

	Per cent
Insoluble	51.14
Al ₂ O ₃	34.68
Fe ₂ O ₃	.12
TiO ₂	.32
CaO	.14
MgO	trace
H ₂ O at 100 degrees centigrade.....	.48
H ₂ O at red heat.....	10.84

Complete Analysis

	Per cent
SiO ₂	44.76
Al ₂ O ₃	42.38
Fe ₂ O ₃	.18
TiO ₂	1.04
CaO	.18
MgO	trace
K ₂ O and Na ₂ O.....	.22

ANALYSIS OF LIGNITE

	Per cent
Moisture	7.30
Volatile combustible matter.....	54.88
Fixed carbon.....	15.48
Ash	22.34
Sulphur	1.60

Analyses of lignite, as given by Moore,⁸ show that the above analysis makes this material fall into the limits of the lowest grade lignite. The analysis of the ash of this lignite is as follows:

ANALYSIS OF LIGNITE ASH

	Per cent
SiO ₂	47.82
Al ₂ O ₃	48.80
Fe ₂ O ₃	trace
TiO ₂	2.40
CaO	.12
MgO	.64
	99.78

This ash burns to a white powder. The volatile matter in this sample (B-385) was determined according to the method for the proximate analysis of coal. The result is probably a little high, on account of mechanical loss.

The analysis of the siliceous material is as follows:

ANALYSES OF SILICEOUS MATERIAL

National Method

	Per cent
Insoluble	89.95
Al ₂ O ₃	6.18
Fe ₂ O ₃	.86
TiO ₂	.70

⁸ E. S. Moore: Coal. John Wiley and Sons, 1922, p. 84.

Complete Analysis

	Per cent
SiO ₂	88.28
Al ₂ O ₃	7.92
Fe ₂ O ₃	.88
TiO ₂	1.76

Screen Test

	Per cent
Plus 60 mesh equals.....	1.15
— 60 plus 80 equals.....	6.26
— 80 plus 100 equals.....	7.98
— 100 plus 200 equals.....	24.86
— 200 equals.....	59.75
	100.00

The presence of lignite intimately associated with the kaolin and bauxite of the Isabella Stewart mine shows that the bauxite was deposited just before swamp conditions existed on the edge of this old peneplain, and shows conclusively that the bauxite was formed on such an old peneplain probably just before the end of this baseleveling period and just before a slight subsidence which permitted the accumulation of the lignite.

According to Hayes,⁹ the Appalachian deposits, of which the above is a typical example, were formed imbedded in residual clay derived from the weathering of limestone. His résumé of this theory is as follows:

"The limestone overlies a great mass of shales (lying 500 to 4,000 feet below the surface), and the formations are intersected by numerous faults, along which water has in the past found easy access to great depths. The shales are made up largely of silicate of aluminum. They also contain considerable iron sulphide in the form of pyrites. It is believed that the surface waters, carrying oxygen in solution, gained access to these shales and, by oxidizing the pyrites, set free sulphuric acid. This, under the conditions present, decomposed the aluminous shales, forming alum and sulphate of aluminum. Ascending currents carried these salts in solution to the surface, and, coming in contact with the limestone during their upward passage, they were decomposed, forming sulphate of lime and aluminum hydroxide, together with basic sulphate of aluminum, which was subsequently changed to aluminum hydroxide on exposure to the air. The aluminum hydroxide thus produced formed a gelatinous precipitate which collected about vents of springs. It was kept in motion by the ascending water and thus formed concentric structures. The reactions indicated above are all known to take place in nature and the process is one which is readily understood."

⁹ C. W. Hayes: Twenty-first Annual Report, U. S. Geol. Survey, part iii, 1899-1900, p. 461.

Hayes's theory of the origin and mode of occurrence of the Appalachian bauxite deposits has been considered correct by Watson,¹⁰ who studied the Georgia deposits in 1904.

As before stated, Watson recognized that the bauxite deposits were formed during a period of baseleveling, and considered the age of this old peneplain to be Eocene. Shearer¹¹ follows Watson and considered the north Georgia deposits to have been formed near the surface during a period when the land was nearly baseleveled, and states this condition existed during Eocene time. Ashley¹² considers the Chattanooga deposits to be of the same type as the Alabama-Georgia deposits, and to be an extension of this field, and that the Chattanooga deposits all occur at approximately the same elevation, but ends in stating that much more extended studies of the Tennessee deposits will be necessary to determine which theory is correct in accounting for their origin and method of formation.

LABORATORY EXPERIMENTS

On boiling both the bentonite from Bragg's quarry and the bauxite from the Isabella Stewart mine with a sulphuric acid, in accordance with the "National method," it is seen from the analyses given on pages — and — that practically all the aluminum goes into solution. The "National method" is as follows:

"Boil for three hours with reflux condenser 2 grams of sample (finely ground) in 20 cubic centimeters of exactly 50 per cent sulphuric acid; solution is then diluted with a little hot water and filtered; the residue is reported as 'insoluble.' The filtrate is received in a 200-cubic-centimeter volumetric flask, diluted to the mark, an aliquot portion taken out and precipitated with ammonia in the usual manner, precipitate ignited and weighed as Al_2O_3 plus Fe_2O_3 . Another aliquot portion is removed, on which iron is determined (volumetrically or colorimetrically) and calculated to Fe_2O_3 . (Al_2O_3 plus Fe_2O_3) — Fe_2O_3 equals Al_2O_3 ."

The results obtained by treating the two minerals in this manner are as follows:

¹⁰ Thomas H. Watson: Bauxite deposits of Georgia. Georgia Geol. Survey, 1904, p. 126.

¹¹ H. K. Shearer: Bauxite and fullers' earth of coastal plain of Georgia. Georgia Geol. Survey, Bull. 31, 1917, p. 23.

¹² George H. Ashley: Bauxite mining in Tennessee. Tennessee Geol. Survey, Resources of Tennessee, vol. i, 1911, pp. 211-219.

"National Method"

		Bentonite	Bauxite
Insoluble	.....	56.80	5.49
Soluble.	{ Al ₂ O ₃	17.01	60.00
	{ Fe ₂ O ₃	2.87	1.04
	{ TiO ₂	.12	.56
	{ CaO	4.40	.....
	{ MgO	4.26	.....
	{ H ₂ O	14.54	32.68
		100.00	99.77

A small amount of sulphuric acid in the ground-waters would dissolve out the constituents listed as soluble in the above analysis, and the waters carrying these salts in solution, on coming to the surface in a region of acid swamp or surface water containing tannic acid, etcetera, would readily deposit them so as to form the bauxite deposits of the Chattanooga section.

Laboratory experiments made on a sulphuric acid solution of bentonite show that on treatment with tannic acid the alumina is precipitated. The experiment was as follows:

Samples of bentonite were prepared by treating with 25 per cent sulphuric acid, boiled 3 to 4 hours with reflux condenser, filtered; filtrate evaporated about to dryness, taken up in water, boiled, and filtered.

Samples were all made up to 500 cubic centimeters and contained about 1 per cent free sulphuric acid.

The tannic acid used was "tannic acid—pure," from Eimer and Amend, New York. The formula is C₁₄H₁₀O₉. This is a monobasic organic acid; may also be written H.C₁₄H₉O₉ or C₁₃H₉O₇.COOH.

Sample number 1 contains sulphuric acid soluble matter from 25 grams bentonite plus 5 grams tannic acid (dissolved in a little water) and the whole diluted to 500 cubic centimeters (5 per cent bentonite plus 1 per cent tannic acid).

Sample number 2: 5 per cent bentonite plus 0.5 per cent tannic acid.

Sample number 3: 5 per cent bentonite plus 0.1 per cent tannic acid.

Sample number 4: 2 per cent bentonite plus 1.0 per cent tannic acid.

Sample number 5: 2 per cent bentonite plus 0.5 per cent tannic acid.

Sample number 6: 2 per cent bentonite plus 0.1 per cent tannic acid.

Sample number 7: 1 per cent bentonite plus 1.0 per cent tannic acid.

Sample number 8: 1 per cent bentonite plus 0.5 per cent tannic acid.

Sample number 9: 1 per cent bentonite plus 0.1 per cent tannic acid.

The above samples were put up in 500-cubic-centimeter flasks, stop-

pered with rubber stoppers containing capillary tubes, and allowed to stand in the laboratory.

Within two days a residue appeared in flasks number 1, number 4, and number 7. After four days residues appeared in number 2, number 3, and number 5, and after a week in number 6, number 8, and number 9. From then on no marked change appeared to occur in any of the samples. After standing for 8½ months, they were filtered, residue washed thoroughly with cold water (residue consisting of organic matter and alumina with a faint trace of iron), and alumina determined in this residue.

Sample number	Weight of bentonite	Weight of tannic acid	Weight of Al_2O_3 precipitated	Per cent of Al_2O_3 precipitated
1.....	25 grams	5 grams	.0038 gram	.07
2.....	25 grams	2.5 grams	.0034 gram	.07
3.....	25 grams	0.5 grams	.0036 gram	.07
4.....	10 grams	5.0 grams	.0034 gram	.17
5.....	10 grams	2.5 grams	.0012 gram	.06
6.....	10 grams	0.5 grams	.0010 gram	.05
7.....	5 grams	5.0 grams	.0028 gram	.28
8.....	5 grams	2.5 grams	.0011 gram	.11
9.....	5 grams	0.5 grams	.0010 gram	.10

Assuming that bentonite is 20 per cent alumina.

Now, if we arrange these with reference to the ratio of tannic acid to alumina (weights) in sample treated, we notice as follows:

Sample number	Weight of tannic acid divided by weight of alumina ratio	Precipitated Al_2O_3 (per cent)
7.....	5.0 times as much tannic acid as alumina	.28
4.....	2.5 times as much tannic acid as alumina	.17
8.....	2.5 times as much tannic acid as alumina	.11
5.....	1.25 times as much tannic acid as alumina	.06
1.....	1.0 times as much tannic acid as alumina	.07
2.....	.5 times as much tannic acid as alumina	.07
9.....	.5 times as much tannic acid as alumina	.10
3.....	.1 times as much tannic acid as alumina	.07
6.....	.1 times as much tannic acid as alumina	.05

From this it appears that the greater the ratio of tannic acid to alumina present, the greater the precipitated alumina. The relative concentration of the solution seems to be of minor importance. A preliminary test was made with a sample containing sulphuric acid soluble matter from .5 gram bentonite plus 1 gram of tannic acid. Thirty days

after the solution was made the sample was filtered. The alumina obtained was 2.20, or 0.11 gram. The percentage of (Al_2O_3) alumina precipitate to the entire alumina in bentonite was 11 per cent. In this sample the ratio of tannic acid to alumina is 10, or twice as great as in any of the $8\frac{1}{2}$ -month tests; yet the percentage Al_2O_3 is 11 per cent, which follows the ratio as shown above, except the results in this case seem excessively high.

GENERAL CONCLUSIONS

These experiments show that the bentonite may very readily be the source of the alumina in the bauxite deposits of the Appalachian region. It is known that this bentonite bed occurs from Birmingham on the south to Ohio on the north and probably over the entire area of the Lowville sea;¹³ wherever these bentonite beds occur in a faulted region, not far below the surface of one of our old or recent peneplains, one might well look for bauxite deposits.

It is considered that the Chattanooga district bauxite deposits obtained their alumina from the bentonite beds of Ordovician age, and that the deposits were formed on an old peneplain at the beginning of the Pleistocene period.

DISCUSSION

C. A. BONINE: I would like to ask Mr. Nelson to clear up a matter for me. Is the dolomite older than the rocks thrust over on it?

NELSON: Yes.

BONINE: How does bentonite get over the surface?

NELSON: That is not bentonite. It is bentonitic material mixed with bauxitic material.

A. C. LANE: One of my students found a sample with characteristic sign of oxide deposits in this region.

¹³ Wilbur A. Nelson: Volcanic ash-bed in the Ordovician of Tennessee, Kentucky, and Alabama. Bull. Geol. Soc. Am., vol. 33, 1922, pp. 605-616.

CRYSTALLINE ROCKS OF THE PLAINS¹

BY CHARLES N. GOULD

(Presented before the Society December 29, 1922)

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PRECAMBRIAN CRYSTALLINES

A glance at the geological map of that part of the United States lying between the Mississippi River and the Rocky Mountains will reveal six regions of mountain uplift, namely, the Black Hills, the Ozarks, the Ouachitas, the Arbuckles, the Wichitas, and the Llano Mountains (sometimes called the Central Mineral Region) of Texas. The general structure of all these mountains is essentially the same, being in each case a

¹ Manuscript received by the Secretary of the Society February 7, 1923.

truncated dome. Except in the case of the Ouachitas, the sedimentaries have been removed by erosion over the core of the uplift and the subjacent crystalline rocks have been exposed (see figure 1).

The greater part of the igneous rocks exposed in the cores of these various mountains is Precambrian in age, and the rocks vary considerably, both in composition and in texture. In the Black Hills the crys-

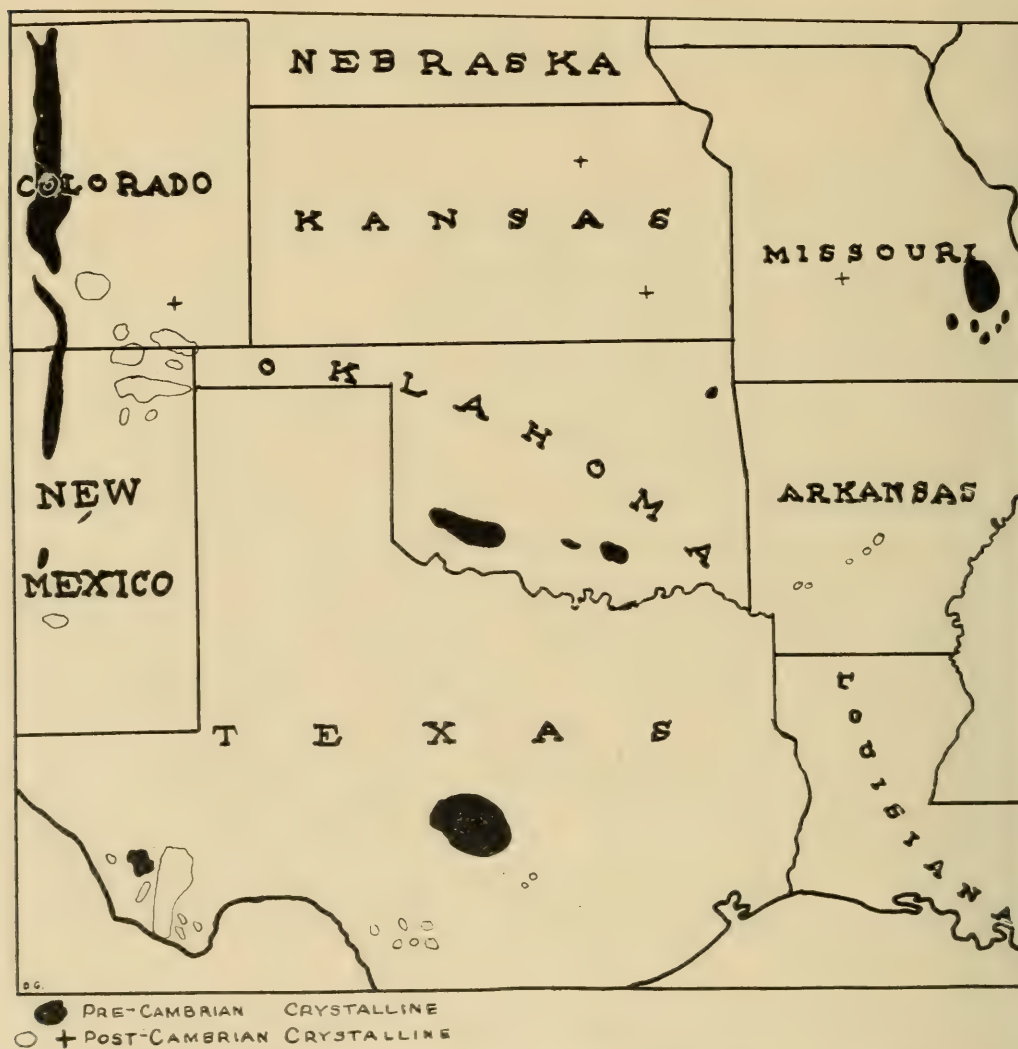


FIGURE 1.—Location of Occurrences of Crystalline Rocks on the Plains

talline rock is largely gneiss, schist, and granite; in the Ozarks it consists chiefly of granite and rhyolite, with intrusive dikes of diabase; in the Arbuckles the igneous rock is chiefly coarse granite and gray and reddish porphyry; in the Wichitas it is largely red and black granite, gabbro, and porphyry, while in the Llano Mountains the igneous rock consists largely of schist and gneiss, with intrusions of granite, gabbro, and diabase.

The sedimentaries exposed, dipping quaquaversally along the flanks of these various mountain ranges, vary in age from Cambrian to Tertiary. In the Black Hills the sedimentary rocks include Cambrian, Ordovician, Carboniferous, Triassic, Jurassic, and Cretaceous sedimentaries; in the Ozarks, Ouachitas, and Arbuckles there are rocks of each of the Paleozoic systems. In the Wichitas and Llanos, Cambrian, Ordovician, and Carboniferous sediments are exposed.

From time to time each of these mountains has been studied in much detail by various geologists, and there has accumulated a large amount of literature on each of the groups. It is not the intention at this time to enter into the discussion of the crystalline rocks in the mountain uplifts, nor, in fact, to do more than to briefly mention their occurrences.

CRYSTALLINES OF LATER AGE

GENERAL STATEMENT

Besides the Precambrian igneous rocks which occupy the cores of the various mountain ranges, there are on the plains several widely scattered regions in which occur crystalline rocks of Paleozoic or later age. The greater part of these rocks are considered to be intrusive. They vary greatly, both in composition and in character.

OCCURRENCES NEAR THE ROCKY MOUNTAINS

Along the western margin of the Great Plains, and usually at no great distance from the east flanks of the Rocky Mountains, there are numerous exposures of crystalline rocks. The Texas Geological Survey¹ lists 16 ranges or groups of mountains in Trans-Pecos, Texas, south of the line of the Texas and Pacific Railroad, which contains igneous rocks, the greater part of which are intrusives. Basalt dikes are known to occur in southeastern New Mexico, where they cut the Tertiary; also near Santa Rosa, in Guadalupe County, east central New Mexico, where the volcanic rock penetrates Triassic Redbeds.

The most notable example of volcanic action on the plains is the Raton Mesa region of northeastern New Mexico and southeastern Colorado, extending from near the foothills of the Rockies eastward for a distance of 100 miles, into extreme northwestern Oklahoma.² There are in this region scores, possibly hundreds, of volcanic cones. Some are comparatively young, like Capuline, which stands 1,300 feet high and is a perfect type of cinder cone, with a crater a quarter of a mile in diameter near

¹ For references see page 558.

its summit. Others are much older, like Sierra Granda, which, although it now stands 2,500 feet above the plain, is so old that the crater has been almost wholly destroyed by erosion. There are in this region great numbers of surface lava flows, many of which now form high mesas, such as Raton, Johnson, Barillo, Mesa de Maya, Bartlett, and Chicorica.

Still farther north, along the Rocky Mountain front, is the Spanish Peaks country, with its wonderful system of radiating basalt and monzonite porphyry dikes; also in the region of Tertiary rhyolites near Castle Rock, between Denver and Colorado Springs.

OCCURRENCES IN THE ARKANSAS-TEXAS REGION

In central Arkansas there are a number of exposures of intrusive igneous rocks, which have penetrated the sedimentaries, sometimes the Paleozoics of the Ouachita region and sometimes the Cretaceous of the Coastal Plains. Crystalline rocks exposed south and southeast of Little Rock and near Benton, some 20 miles southwest of Little Rock, are chiefly syenite, known locally as gray granite. These rocks are of particular importance to the economic geologist on account of the fact that, associated with them and with the adjacent Tertiary sediments, are the most important known deposits of bauxite in America. In the Ouachita Mountain region igneous rocks, chiefly syenite, are found in Magnet Cove, about 12 miles east of Hot Springs. Scattering basic dikes of later age than the syenites are also found from the syenite area near Little Rock, westward to within about 30 miles of the Oklahoma-Arkansas boundary. In Pike County there are four small exposures of peridotite which form the source of the Arkansas diamonds.³ According to Drake, it is generally believed that the syenites and Pike County peridotites were intruded during middle Cretaceous times, probably during the land interval separating the upper and lower Cretaceous, while the basic dikes of the central Ouachita region are probably Tertiary in age.

Along the Balcones fault zone, in southwestern Texas, there are numerous exposures of intrusive igneous rocks, consisting largely of basalt and phonolite. These rocks were probably brought to the surface in very late Cretaceous or early Eocene times. The chief exposures are near Austin⁴ and in Uvalde and Kinney counties. In discussing the occurrence of these intrusions in the Uvalde region, Vaughan says⁵ that no surface flows of lava are known, but that the intrusions may be divided into the following classes: (*a*) bosses, stocks, or necks; (*b*) laccoliths; (*c*) laterally intruded sheets, and (*d*) dikes. Something like 65 separate exposures of igneous rocks may be noted on the Uvalde quadrangle.

OHIO VALLEY-BALCONES LINE OF DISTURBANCE

In the President's address before this Society last year,⁶ Professor Kemp warns us, and reiterates the warning, that we are never safe from igneous rocks. The statement was made in connection with his reference to the row of peridotite dikes which occurs along a line extending southwestward from western New York, crossing Pennsylvania and Kentucky, as far as the dikes in Pike County, southwestern Arkansas. This row of dikes, especially as they outcrop in Pennsylvania and Kentucky, has also been noted by James H. Gardner in his paper published in the bulletin of this Society in 1915,⁷ in which he calls attention to a practically continuous line of stratigraphic disturbance in the Ohio Valley, extending from the Appalachian plateau in Pennsylvania to the Ozark Mountains, a distance of over 500 miles. In Pennsylvania and northern West Virginia this structure is known as Chestnut Ridge anticline; in southern West Virginia it is the Warfield anticline; in eastern Kentucky it is the Campton anticline; farther west it is the Kentucky River-Dividing Ridge fault; in western Kentucky it is the Rough Creek uplift, while in Illinois it is the Shawneetown and Bald Hill anticlines.

While keenly recognizing the fatal fascination of long-distance correlation, it has occurred to me that this line of weakness, characterized by faults, folds, igneous dikes, and other earth movements, all of them indications of lines of weakness, might possibly be carried a step further.

Udden, Baker, and Böse,⁸ in discussing the Austin-Uvalde occurrences of igneous rocks along the Balcones fault zone, have suggested that the Arkansas dikes belong to the same line of igneous activity. They say:

"This belt is a portion of a larger belt of igneous activity which extended from the Arkansas River at Little Rock, Arkansas, west-southwestward to beyond the Rio Grande—a belt in which the igneous rocks are characterized by the presence of the minerals nepheline and augite."

In other words, Kemp ties up the Arkansas dikes to New York, while the Texas geologists tie them to the Uvalde intrusives. The question naturally arises, Who is right? Obviously, both may be right. The idea that there may be a transcontinental line of weakness, of which the Ohio Valley disturbance, the Balcones fault zone, and the various igneous dikes are all visible expressions, is therefore presented at this time with the hope that it may invite suggestion and criticism.

In this connection Mr. Gardner says, in a letter dated December 6, 1922:

"Since the New York-Pennsylvania-Kentucky zone is so long, and since the other zone is correspondingly long, and since the two are more or less lined up, it certainly does look like it may be a transcontinental feature.

"The Ozark region of isostatic adjustment could easily be an area related to it or a swell on it. The Ozark uplift being a long time in isostatic equilibrium, at a later period this long diastrophic disturbance could easily be an expression of adjustment running from Appalachian folding (recurrence)



FIGURE 2.—Relation of hypothetical Balcones-Arkansas-Ohio Valley Line of Weakness to adjacent Mountain Masses; also Exposures of igneous Rock

down across the Cincinnati uplift and across or adjacent to Ozark uplift and on down east of Llano-Burnett into Mexico. I recall an expression of Chamberlain to this effect: 'diastrophism works against isostasy,' which is worth thinking about in this connection."

Professor Kemp, however, is inclined to be rather cautious in this correlation. In a letter December 12, 1922, he says:

"I have never attempted to plot in detail the peridotite dikes of Arkansas, nor have I ever in my own mind connected them with the Balcones fault zone of Texas. . . . This is also true of the others from this region clear through

to New York. I do not think they are along connected lines of disturbance, but follow the local lines of weakness. I know that near Ithaca they are parallel with the master joints."

The map presented (figure 2) will show the relation of the Balcones-Arkansas-Ohio Valley line of weakness and the igneous exposures to the adjacent mountain masses.

Another thought comes to mind. It is possible that the New Madrid earthquake, the center of which was very near, if, indeed, not in direct line with this zone of weakness, might have been caused by slipping along this fault zone.

SCATTERED OCCURRENCES OF CRYSTALLINES

GENERAL STATEMENT

In addition to the Precambrian crystalline rocks exposed in the mountain uplifts, and the various post-Cambrian intrusives occurring either in the Arkansas-Texas zone of weakness or in the region near the base of the Rockies, there are on the plains several localities where crystalline rocks of various sorts have been brought to the surface. One thinks at once of the Sioux Falls quartzite and associated rocks, which outcrop over considerable areas in Minnesota and South Dakota and which have been found in many wells in regions adjacent to the outcrops of these crystallines.

There are at least five places in the plains where very small and inconspicuous exposures of crystalline rocks occur. These occurrences, which will be discussed in brief detail, will serve to illustrate that Kemp's pronouncement that "we are never safe from igneous rocks, no matter how innocent flat strata look from the surface."

SPAVINAW CREEK, OKLAHOMA

For many years we have known that an exposure of granite occurred along Spavinaw Creek, in Mayes County, eastern Oklahoma. This rock was first mentioned by D. D. Owen, and later visited by Drake,⁹ who referred to it as a granite dike. Snider¹⁰ and others who have published on this locality have generally followed Drake in considering it a dike. The exposures, consisting of red granite which has the general appearance of the granite of the Wichita Mountains, are about 1,200 feet long and 50 feet wide.

Fritz Aurin, who recently studied this exposure, says¹¹

"It is not an igneous dike, as is generally thought, but is a granite peak of the old Precambrian basement. Overlying the granite is a siliceous, dolomitic

limestone several hundred feet in thickness correlated with similar limestones of Cambro-Ordovician age in other localities."

CAMDEN COUNTY, MISSOURI

In Camden County, south central Missouri, there is a single exposure of igneous rock. Arthur Winslow describes it as follows:¹²

"On the Camden and Laclede County line, at the Wheeler mine, in section 32 of township 27 north, range 16 west, is an area of intense local disturbance. With this is associated an erupted dike or boss of pegmatite. Special interest attaches itself to this outcrop, as it is the only one of post-Archean age found in the Mississippi Valley, with the exception of the Mesozoic eruptives of Arkansas. Further, it is the only indication we have that igneous action or metamorphism accompanied the crustal movements of the Ozark uplift. The actual exposure of pegmatite does not exceed a few square yards, and, had it not been that the locality was prospected for lead, its presence might never have been detected.

"The rocks of the dike consist of a graphic granite or pegmatite and of white mica. These do not seem to be disturbed or arranged in any special order, unless it be that the mica prevails near the contact with the surrounding rocks. The dike seems to have the form of a boss or neck, which has pushed its way up through the rocks. It is not probable that this intrusion or eruption ever reached the surface."

Edward M. Shepard says, in a personal communication dated November 2, 1922:

"The pegmatite exposure in Camden County is, without any doubt in my mind, a volcanic dike. The immediate contact with adjoining rocks shows metamorphism in the formation of beautiful yellow, contorted muscovite, schist, and quartzite. The galena in the neighborhood is badly decomposed. The rocks for many acres around, representing the lower formations, either stand on edge or are greatly tilted."

WOODSON COUNTY, KANSAS

On an area of about 120 acres in southern Woodson County, Kansas, granite boulders varying in size up to seven feet in diameter are strewn on the surface. Professor Twenhofel, who has studied these rocks and their mode of occurrence, was first of the opinion that these "boulders reached the position in which they are found through the agency of ice, either glacial or floating, but more probably the latter."¹³ Later studies of metamorphism in adjacent areas, however, have caused him to suggest that possibly "the facts may be explained on the hypothesis that the boulders mark the weathered outcrop of a dike."¹⁴

In a letter dated November 1, 1922, Professor Twenhofel says:

"The possible occurrence of igneous rocks in Kansas, which are known to me from personal observation, are at Silver City and near Rose, both in Woodson County. Each occurrence is associated with, and in each instance perhaps related to, a dome or anticline which, for the eastern portion of Kansas, has comparatively steep dips.

"The anamorphosed sediments at Silver City are best explained by the occurrence of an igneous intrusion at no great distance beneath the surface. At Rose the igneous rocks are at the surface and consist of granite blocks with linear distribution. Holes drilled to the south of these blocks are not known to have penetrated igneous rocks, although some of them were but a short distance away. . . . I have made the interpretation that these granite blocks may possibly have reached their present positions through deposition from floating ice. Their marine distribution, the association with decided doming of the strata, the reported occurrence of anamorphism, and the nearness to the occurrence at Silver City support the hypothesis that the Rose granites represent an intrusion which may have occurred at the same time as that at Silver City. If the latter be the correct interpretation, it is probable that a well properly located would encounter similar granites at Silver City."

RILEY COUNTY, KANSAS

A single exposure of igneous rock in west central Riley County, Kansas, has recently been described by Moore and Haynes.¹⁵ This exposure, which lies about 20 miles northwest of Manhattan, is an outcrop of a dark green rock, an igneous breccia, forming a low, domelike, grass-covered mound with a maximum elevation of about 30 feet. The total area of the mound is not more than one acre, and the weathered fragments of the dark green rock were not found more than 100 feet beyond the limits of the symmetrical mound. The conclusion is reached that the mass is a rather small volcanic neck or pipe, of post-Permian age. Mr. Howard Tomlinson, who studied the rock in this section, pronounces it kimberlite or porphyritic peridotite.

LAMAR, COLORADO

In southern Prowers County, southeastern Colorado, there is an exposure of igneous rock which Prof. R. D. George, in a personal communication dated November 8, 1922, describes as follows:

"South of Lamar there is a laccolithic area in the southeastern part of township 27 south, range 46 west. The main part of the igneous area is in section 35, but extends over into section 36, and, according to a new survey made, may extend into sections 1 and 2 of township 28 south, range 46 west. The rocks of the main laccolithic bodies are very basic syenitic types. . . . Associated with the laccoliths are 50 or more dikes of various lengths and touching the adjacent corners of the four townships. On one of these areas is a body of porphyritic granite . . . 100 yards long and 15 to 20 yards

wide. Gilbert, in *Journal of Geology*, volume IV, page 821, says: 'Fragments of various rocks are included in the laccoliths and dikes, and are of interest as revealing the nature of the lower lying terranes through which the ascending liquid passed. Besides sandstones and shales similar to those constituting the wall rocks, the most abundant as well as the most notable rock is a porphyritic granite with conspicuous crystals of gray feldspar.' This suggests his belief that the granite is an inclusion in or mass floated up by the basic igneous rocks forming the laccolith. There are at least three granite laccoliths, but I am not entirely certain that the two smaller granite masses are in place. While I have made no petrological examination of the granite, its general appearance suggests quartz monzonite rather than a true granite."

SUBSURFACE CRYSTALLINE ROCKS

GENERAL STATEMENT

It is, however, chiefly with subsurface igneous rocks that this paper is concerned. We may safely say that within the past five years our knowledge of the subsurface geology of the Great Plains, especially in certain parts of Oklahoma, Kansas, and Texas, has increased several hundred per cent. This condition has been largely brought about, either directly or indirectly, by the work of the geological departments of the various oil companies. In these States the geologist is now considered as an integral part of any oil organization, and his advice is not only sought, but acted upon, by men making large investments of time and money.

A number of highly trained and very efficient men, young men for the most part, in these States are now devoting the greater part of their time to subsurface work. Logs of wells are studied and compared, and in this manner many subsurface structures of which there are no surface indications sometimes have been plotted. Considerable literature is already accumulating on the subject, but the most comprehensive paper on subsurface crystallines was published by Sidney Powers.¹⁶

The net result of the work of the various geologists who are now working on subsurface problems has been to throw a vast amount of new light on the underground stratigraphy and structure of the region. Unfortunately, much of the material collected is not yet available to the public, largely for the reason that relatively few of the oil companies have yet reached the stage where they can afford to be philanthropists; also, many of the managers of these companies, being anything but scientific men, have not yet been brought to appreciate the true worth of broadly disseminated scientific investigation. There is still much needless and expensive duplication of work and much attempt to conceal data which would be of the greatest value in the solving of vital problems. Nevertheless, each year more and more new facts are coming to light and the

members of the geological fraternity are gradually accumulating a vast amount of useful information.

Ten years ago relatively little was known regarding the subsurface formations of the Great Plains. Academically, the geologist knew, of course, that granite or other crystalline rocks underlaid all this region, but little was known as to the character and thickness of the sedimentaries. Occasionally a driller reported granite in a deep well, but at that time neither the oil man nor the geologist paid much attention to his statements.

NEMAHA MOUNTAINS

During the years 1914-1915 several wells located on well-defined anticlines in northern Kansas began to encounter crystalline rocks, and since that time something like 30 wells have been drilled to granite in this State. The results have shown a very peculiar geological phenomenon, namely, the presence of a buried granite ridge, now known to extend from somewhere near the mouth of Platte River, in southeastern Nebraska, entirely across the State of Kansas and into northern Oklahoma, a distance of over 200 miles. Prof. R. C. Moore, who is our best authority on the subject, has very fully discussed the matter in two publications, one in the bulletin of the Geological Survey of Kansas¹⁷ and the other a paper read before this Society.¹⁸ He has named this subsurface ridge the Nemaha Mountains. Professor Moore states that at a point near the Kansas-Nebraska line "the crystalline rocks approach to within 550 feet of the surface and attain an elevation of nearly 600 feet above sea level" The elevation of the crest of the buried ridge gradually declines toward the south, granite being encountered at 3,420 feet some 25 miles north of the Oklahoma line and at 4,800 feet near Newkirk, Oklahoma. In addition to the writings by Moore, there has already grown up quite a literature on the granite ridge, particularly the writings of Haworth,¹⁹ Taylor,²⁰ Powers,²¹ and Wright.²²

Studies made by different geologists of the records of wells which touched crystalline rocks have shown some very interesting facts. While the data are still far from complete, enough facts are now available to postulate the presence of several granite ridges on the plains other than the Nemaha Mountains, already discussed.

AMARILLO MOUNTAINS

In 1905 the writer discovered along the Canadian River, in the northern part of the Panhandle of Texas, a series of large structures. These were duly embalmed in the literature and straightway forgotten.²³ In

1917, happening to mention the fact to some business men of Amarillo, their interest was aroused, with the result that the region was revisited and a careful survey made of the largest of these structures, the John Ray Dome, in Potter and Moore counties, some 20 to 30 miles north of Amarillo. It was found that this dome had an area of over 100 square miles, with a lift of about 500 feet. The first well drilled on this structure encountered gas, and since that time about a dozen gas wells have been drilled on this dome, producing up to 107,000,000 cubic feet of gas daily. Wells drilled on the 6666 dome in Carson and Hutchinson counties have produced both gas and oil. Other domes have proved to be nonproductive.

One very interesting thing about these structures is that as more and more wells have been drilled we have learned that they are superimposed upon buried crystalline rocks. The greater number of the wells reach either an arkosic sand or felsite, somewhere between 2,000 and 3,000 feet, and at least two wells on each of the three domes—Bravo, John Ray, and 6666—appear to have penetrated solid granite.

Now, by projecting the main axis of the Arbuckle-Wichita uplift to the northwest, it will be seen that these domes are practically in line with this projection; also, there are four granite wells in southwestern Oklahoma and the eastern part of the Panhandle, making in all ten granite wells in practically a straight line with the Arbuckle-Wichita axis.²⁴ In the light of present knowledge, therefore, it would seem safe to postulate a buried granite ridge extending from the west end of the Wichitas northwestward for a distance of at least 200 miles.

In this connection it may not be amiss to call attention to the fact that granite has been encountered in wells near Caney, Oklahoma, southeast of the Arbuckle granite. It has been suggested that the Arbuckles, and possibly the Wichitas, are connected with Llanoria.²⁵ At any rate, the line along which crystalline rocks, either surface or subsurface, occur extends from southeastern Oklahoma, along the axis of the Arbuckle and Wichita Mountains, and entirely across the Panhandle of Texas, as far as northeastern New Mexico, a distance of nearly 400 miles.

If a name be desired for this buried mountain range northwest of the Wichitas, perhaps none better can be found than the name "Amarillo Mountains." Powers has already used the term "Amarillo Hills" to describe the buried structures under the oil- and gas-producing structures in this region,²⁶ but he did not include the gap between the 6666 dome in Carson County, Texas, and the Wichitas.

RED RIVER UPLIFT

Powers has also called attention to several granite wells along Red River, in northern Texas and southern Oklahoma, in what he calls the Red River uplift, extending eastward from the Petrolia oil field. The presence of at least five wells, more or less in line, which have reached granite, in this region would lead to the assumption of the possibility of the presence of a buried ridge at this place. Figure 3 shows the location of the Nemaha and Amarillo Mountains and of numerous wells which have touched granite.

BURIED GRANITE RIDGE IN NEW MEXICO

John L. Rich has described a "buried granite mountain range underneath the western margin of the Great Plains, 30 to 70 miles east of the Front Range of the Rockies,"²⁷ reaching from Corona, New Mexico, northeastward for a distance of nearly 300 miles. Mr. Rich bases his conclusions on certain outcrops of igneous rocks as well as on granite in several wells along the broad geanticline which separates the synclinal basin east of the Front Range from the long monoclinical eastward dip of the rocks across the plains. Regarding this matter, Mr. Rich says in a letter dated December 4, 1922:

"East of the Estancia Valley of New Mexico, for a distance of over 50 miles north and south, there are outcrops of granite and other rocks of the basement complex which represent the tops of a mountain range which was buried under sediments of Permian age and later partly exhumed. The Hills of Pedernal are monadnocks, near the northern end of the exposed portion of this range. A few miles north of them, in the area covered by the Permian sediments, several wells have encountered granite at shallow depths immediately below the Permian rocks. At the Anton Chico well, township 11 north, range 19 east, granite was found at about 2,000 feet immediately beneath the Permian Redbeds. In a well drilled by the Continental Oil Company, in township 31 north, range 33 east, on the broad anticlinal area east of the Raton coal basin, granite was struck immediately below the Redbeds at about 2,500 feet. These facts, taken in connection with the general structure of the region, lead to the conclusion that an extensive mountain range of Pennsylvanian or early Permian age lies buried under the plains 30 to 70 miles east of the present Front Range of the Rocky Mountains."

MISCELLANEOUS GRANITE WELLS

From the map shown in figure 3, it will be noted that there are quite a number of granite wells in the region west of the Ozarks. In Kansas, six wells are reported east of the Nemaha Mountains. In northeastern Oklahoma there are 15 granite wells; also six wells in Missouri and two

in northwestern Arkansas. Some of these wells, as, for instance, two in the Cushing field, are known to be on well-marked anticlines, which have yielded large amounts of petroleum, while others occur where there is little surface indication of structure and where no oil has been found.

It must be remembered that out of several thousand wells drilled in southeastern Kansas and northeastern Oklahoma only a very few have



FIGURE 3.—Location of buried Granite Ridges in Kansas, Oklahoma, and Texas; also Location of Wells which have reached Granite

passed entirely through the sedimentaries. The common interpretation of the presence of granite in these wells is either that they were drilled at a place where the granite basement was comparatively near the surface, or that the well chanced to be located over a buried monadnock.

I realize very keenly the tendency to derive conclusions from insufficient data, and to postulate buried ridges in likely regions. While it may be a geometrical axiom that three points in a row indicate a straight line,

it is not necessarily true that three granite wells in a row mark a buried ridge. One might easily take a granite well map of southeastern Kansas and northeastern Oklahoma and draw lines in every direction, some of which might possibly be located along a buried ridge.

The data set forth in this paper have been secured from many sources, chiefly from State geologists and from the chief geologists of the various oil companies, as well as from many private investigators, to each of whom is due my sincere thanks. No pretense is made to completeness in this paper, for new granite wells are constantly being drilled. Doubtless many wells which have encountered granite have never come to the attention of geologists, while in many other cases the information can not yet be divulged for "business reasons." This paper must, therefore, be considered nothing more than a progress report. However, it is believed that the locations hereby given will represent in a fair manner our present available knowledge of the subject.

LIST OF GRANITE WELLS

The following tentative list shows the location and depth of the granite wells of which the writer now has a record, in the States of Nebraska, Kansas, Missouri, Arkansas, Oklahoma, Texas, and eastern New Mexico:

Nebraska

Depth, feet *

Township 1 north, range 12 east	522	Pawnee County.
2 north, range 12 east	600	Pawnee County.
3 north, range 12 east	600	Pawnee County.

Kansas

Depth, feet

Section 36, township 32 south, range 2 east	3,420	Sumner County.
7, township 22 south, range 4 east	3,355	Marion County.
1, township 23 south, range 4 east	3,530	Butler County.
11, township 26 south, range 4 east	2,675	Butler County.
12, township 26 south, range 4 east	2,805	Butler County.
17, township 28 south, range 4 east	2,800	Butler County.
2, township 7 south, range 5 east	2,520	Riley County.
25, township 20 south, range 5 east	3,040	Marion County.
12, township 23 south, range 5 east	2,500	Butler County.
14, township 23 south, range 5 east	2,331	Butler County.
16, township 23 south, range 5 east	2,735	Butler County.
26, township 23 south, range 5 east	2,545	Butler County.
6, township 24 south, range 5 east	....	Butler County.
5, township 18 south, range 6 east	2,515	Chase County.

			Depth, feet	
Section 15,	township 18 south, range 6 east	2,427	Chase County.	
19,	township 18 south, range 6 east	2,410	Chase County.	
7,	township 19 south, range 6 east	2,585	Chase County.	
24,	township 15 south, range 7 east	2,512	Morris County.	
11,	township 16 south, range 7 east	1,900	Morris County.	
34,	township 17 south, range 7 east	2,506	Morris County.	
24,	township 17 south, range 7 east	2,092	Morris County.	
4,	township 18 south, range 7 east	2,110	Chase County.	
34,	township 19 south, range 7 east	1,805	Chase County.	
2,	township 20 south, range 7 east	1,890	Chase County.	
35,	township 27 south, range 8 east	3,470-3,855	Greenwood Co.	
24,	township 9 south, range 9 east	1,850	Pottawatomie Co.	
28,	township 10 south, range 9 east	928	Waubaussee Co.	
26,	township 10 south, range 9 east	958-1,050	Waubaussee Co.	
1,	township 11 south, range 9 east	1,180	Waubaussee Co.	
12,	township 10 south, range 10 east	2,300	Waubaussee Co.	
19,	township 3 south, range 11 east	940	Nemaha County.	
34,	township 6 south, range 11 east	960	Pottawatomie Co.	
6,	township 2 south, range 12 east	600	Nemaha County.	
6,	township 2 south, range 12 east	600	Nemaha County.	
22,	township 29 south, range 13 east	2,500	Wilson County.	
..,	township 14 south, range 15 east	2,835	Osage County.	
17,	township 25 south, range 15 east	1,125	Woodson County.	
29,	township 26 south, range 17 east	2,405	Woodson County.	
13,	township 9 south, range 19 east	3,175	Jefferson County.	
34,	township 29 south, range 19 east	2,035	Neosho County.	
29,	township 25 south, range 20 east	1,827	Allen County.	
16,	township 17 south, range 23 east	2,260	Miami County.	
13,	township 33 south, range 23 east	1,761	Cherokee County.	

Missouri

	Feet
Phelps County, Rolla.....	1,800
Jackson County, Carthage.....	1,800
Jackson County, Raytown.....	2,348
Laclede County, Lebanon.....	1,900
Howell County, Pomona.....	2,000

Arkansas

Washington County, township 15 north, range 31 west.
 Benton County, township 10 north, range 31 west.

Oklahoma

				Depth, feet	
Section 35,	township 19 north,	range 23 east	1,776	Cherokee County.	
19,	township 25 north,	range 20 east	1,925	Craig County.	
28,	township 15 north,	range 19 east	3,371	Muskogee County.	
34,	township 29 north,	range 19 east	2,015	Craig County.	

		Depth, feet	
Section 2,	township 23 north, range 19 east	1,540	Mayes County.
4,	township 15 north, range 18 east	3,235	Muskogee County.
4,	township 15 north, range 18 east	2,980-3,037	Muskogee County.
35,	township 20 north, range 17 east	480	Rogers County.
14,	township 20 north, range 17 east	1,226	Rogers County.
27,	township 27 north, range 16 east	2,070	Nowata County.
31,	township 22 north, range 15 east	2,765	Rogers County.
30,	township 28 north, range 13 east	2,548	Washington Co.
22,	township 29 north, range 13 east	2,500	Washington Co.
25,	township 25 north, range 12 east	2,340	Osage County.
22,	township 19 north, range 11 east	3,071	Tulsa County.
25,	township 23 north, range 8 east	3,000	Osage County.
22,	township 19 north, range 7 east	3,760	Creek County.
22,	township 17 north, range 7 east	3,670-3,700	Creek County.
17,	township 17 north, range 7 east	3,667	Creek County.
18,	township 28 north, range 3 east	4,790	Kay County.
35,	township 6 south, range 5 west	2,240	Jefferson County.
14,	township 7 south, range 6 west	2,600-2,760	Jefferson County.
15,	township 1 south, range 15 west	1,400	Tillman County.
35,	township 3 south, range 16 west	2,985	Tillman County.
31,	township 6 north, range 17 west	730	Kiowa County.
31,	township 4 north, range 18 west	515-700	Kiowa County.
1,	township 5 north, range 18 west	1,232	Kiowa County.
29,	township 7 north, range 20 west	3,000	Kiowa County.
34,	township 7 north, range 20 west	900	Kiowa County.
8,	township 6 north, range 20 west	850	Kiowa County.
17,	township 5 north, range 21 west	1,400-1,730	Greer County.
35,	township 6 north, range 21 west	380	Greer County.
9,	township 7 north, range 22 west	1,640	Greer County.
36,	township 6 north, range 22 west	840	Greer County.
27,	township 7 north, range 25 west	2,950	Beckham County.
21,	township 8 north, range 26 west	2,415	Beckham County.

Texas

	Feet
Cooke County, 1½ miles northwest of Meunster.....	2,620-2,700
Montague County, 8 miles north of St. Joe.....	3,007
Montague County, 7 miles north of Nocona.....	2,490
Clay County, Petrolia field.....	4,240
Clay County, Petrolia field.....	2,030-2,200
Potter County, Amarillo, Masterson.....	1,600-2,200
Potter County, Amarillo, Masterson.....	2,350-2,370
Carson County, 6666, Panhandle.....	2,800
Oldham County, Bravo.....	2,560
Oldham County, Matador.....	2,380
Oldham County, Shelton.....	2,460
Gray County.	
Collingsworth County.	

A number of wells in the Waco region, in central Texas, reported to have reached a schistose material are purposely omitted from the list for the reason that at this writing there is some difference of opinion as to whether or not these wells actually passed through the sediments.

New Mexico

	Depth, feet	
Section 30, township 11 north, range 19 east	2,000	Guadalupe Co.
6, township 31 north, range 33 east	2,725	Union County.
21, township 11 south, range 18 east	2,000	Lincoln County.
25, township 2 north, range 20 east	2,560	Guadalupe Co.
... township 1 south, range 19 east	2,000	Lincoln County.
8, township 8 north, range 13 east	1,110-1,176	Torrance County.
32, township 20 north, range 31 east	2,400	Union County.
... township 13 north, range 11 east	2,450	Santa Fe County.

DISCUSSION

Mr. R. S. KNAPPEN: It is interesting to note that the so-called "Granite Ridge" of Kansas does not consist of one granitic intrusion but is rather a crystalline complex such as is common in other Pre-Cambrian areas of North America. Cuttings from wells at Winchester, Seneca, and Frankfort (Kansas) have revealed the presence of several types of igneous rocks, ranging from acid pegmatites to gabbros, and of rocks which are in part certainly metamorphosed sediments. In addition to gneiss and schist, which are of doubtful origin, crystalline limestone has been penetrated in the Seneca and Winchester wells.

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CRETACEOUS AGE AND EARLY EOCENE UPLIFT OF A
PENEPLAIN IN SOUTHERN BRITISH COLUMBIA¹

BY W. L. UGLOW

(Presented before the Society December 30, 1922)

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STATEMENT AND SOLUTION OF THE PROBLEM

During a detailed geological survey of the North Thompson Valley map area² in south-central British Columbia, carried out for the Geological Survey of Canada during the summer of 1921, the writer was fortunate enough to encounter certain highly fossiliferous members of the early Tertiary coal-bearing beds which lie at the bottom of the North Thompson River trench from 40 to 55 miles north of the city of Kamloops. In the hope that the topographical location, structure, and age

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² Summary Rept., Geol. Surv. Canada, part A, 1921, pp. 72-106.

of the beds might reveal some precise information concerning the character and date of the Laramide revolution and Tertiary faulting in the southern interior, special importance was attached to their study, and fairly complete collections of fossil plant remains were obtained.

The upland surface into which the North Thompson River has cut a valley about 3,000 feet deep is, at least locally, a peneplain. The age of the coal-bearing beds has been definitely determined as Middle or Upper Eocene. The topographical position of the beds at the bottom of the trench establishes the fact that the peneplain was uplifted about 3,000 feet at or before the beginning of Eocene time. This uplift in the interior plateau country is believed to have synchronized with the mountain-building of the Laramide revolution.

In order to make the evidence on which these conclusions are based available and intelligible to the reader, the following outline of the topography and general geology of the trench is presented:

LOCATION

The North Thompson River runs through south-central British Columbia, rising on the eastern side of the Rocky Mountains in the vicinity of Tête Jaune, and flowing in a general southerly direction for a distance of nearly 200 miles to join the South Thompson at Kamloops. From this point the combined rivers flow westerly and then southerly as the Thompson, joining the Fraser at Lytton.

In this paper only that portion of the North Thompson River which lies within the region of the interior plateaus from its junction with the Clearwater River to its mouth at Kamloops is discussed (figure 1).

TOPOGRAPHY OF THE TRENCH

The present North Thompson River flows through a steep-walled trench, deeply incised in the upland plateau. The trench varies in width from rim to rim from 2 to 10 miles, with an average width of about 5 miles. The bottom of the valley is comparatively even, consisting of broad river flats and low benches. Its width varies from one-half mile to 5 miles, with an average of approximately 2 miles. The average slope of the rocky walls of the valley is about 45 per cent, representing a rise of 45 feet per 100 horizontal.

The elevation of the upland plateau varies in this district from 3,500 to 4,500 feet above sealevel. In general, it is 500 to 600 feet higher on the east than on the west side of the trench. The North Thompson River has an elevation of 1,320 feet at its junction with the Clearwater

and of 1,120 feet at Kamloops. It flows, therefore, along a gradient of 3 feet per mile and is entrenched in the plateau to a depth varying from 2,300 to 3,200 feet.

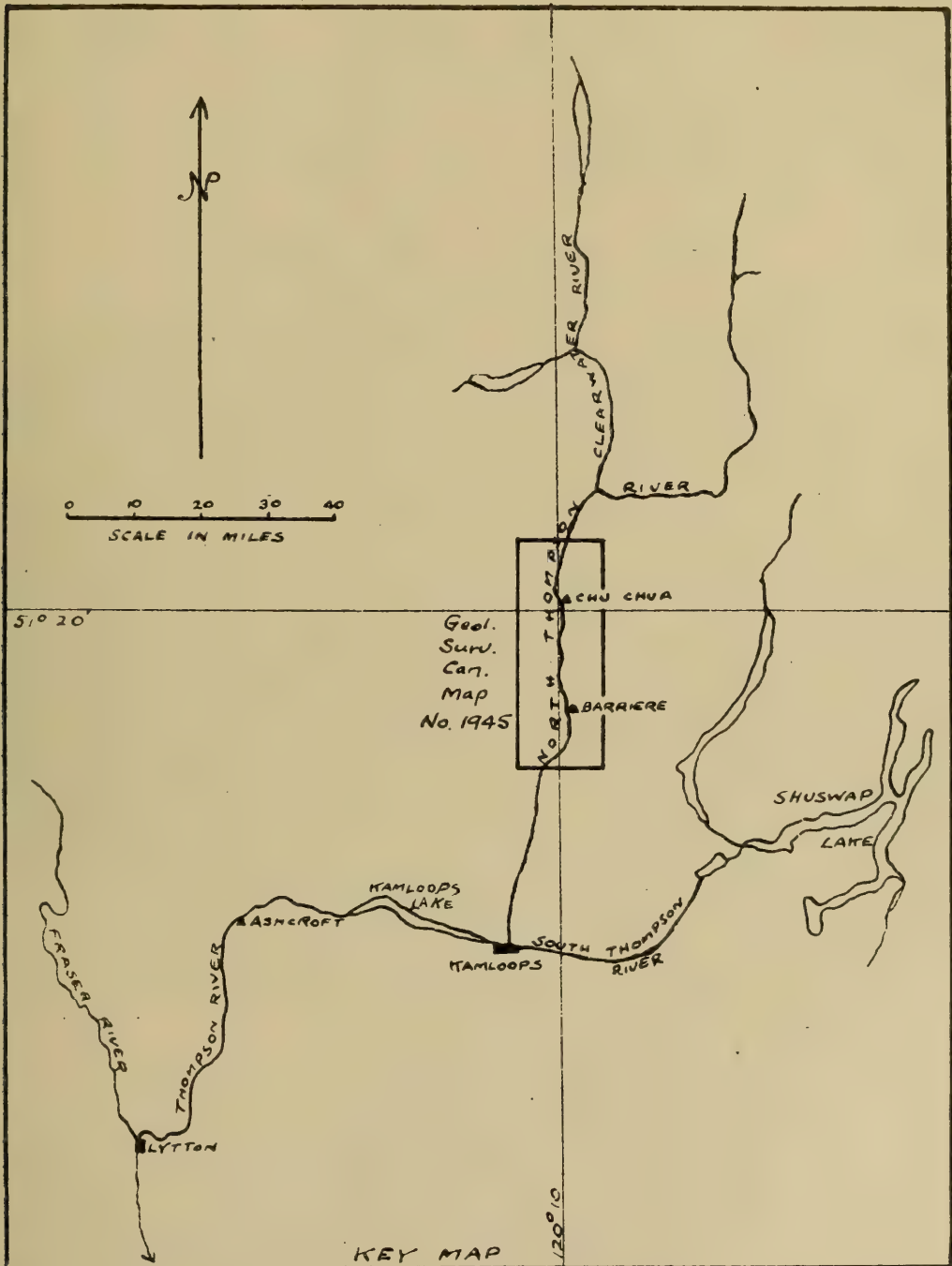


FIGURE 1.—Key Map of Area studied

The upland plateau is characterized by gently undulating ground of low relief, usually drift-covered and thickly timbered. A few bold peaks

and rocky ridges stand as monadnocks in high relief above its general level.

In places where the valley consists of a single depression it is broad and up to 3 miles in width at its base. In other places, as near Louis Creek and Mount Olie, the valley consists of two or more longitudinal trenches, separated from one another by high ridges, whose tops represent isolated remnants of the plateau. In these cases the river is found to flow through one of these subsidiary trenches and is consequently quite constricted (see figure 2).

GENERAL GEOLOGY OF THE TRENCH³

THE ROCK FORMATIONS

The rock formations of the vicinity may be divided into three main groups: (a) the pre-Tertiary complex, (b) the Tertiary sedimentary and volcanic series, and (c) the post-Tertiary lava flows and unconsolidated sediments.

PRE-TERTIARY COMPLEX

This consists of several series of metamorphosed rocks, chiefly sericite, chlorite and hornblende schists, slates, quartzites, crystalline limestones with highly altered volcanic tuffs, and pillow lavas, cut by many stocks, sills, and dikes of gabbro, granite, grandiorite, and a batholith of granite. No fossils have yet been found in the rocks of the complex, so that it is not known whether they belong individually or collectively to the Precambrian or the Paleozoic. The age of the intrusive rocks has not been definitely determined. Some of them may be of Precambrian age, some of them are believed to be Jurassic, and others may even be Tertiary.

The attitudes of the foliated or bedded rocks are not parallel to the main northwesterly Cordilleran trend. They strike east, northeast, or northwest with very little tendency to exhibit any regularity.

TERTIARY ROCKS

These are of two ages—Middle or Upper Eocene and Miocene.

The Eocene, or Chu Chua formation, consists of a series of basal conglomerate (or agglomerate), highly feldspathic arkose, sandy shale, and sub-bituminous coal. These rocks occur in the bottom and along the lower slopes of the North Thompson trench, in isolated erosion remnants, the highest exposures found being at an elevation of about 700 feet above the level of the river (see figure 4). They underlie a few narrow low

³ For full discussion see Summary Rept. Geol. Surv. Canada, part A, 1921, pp. 72-106.

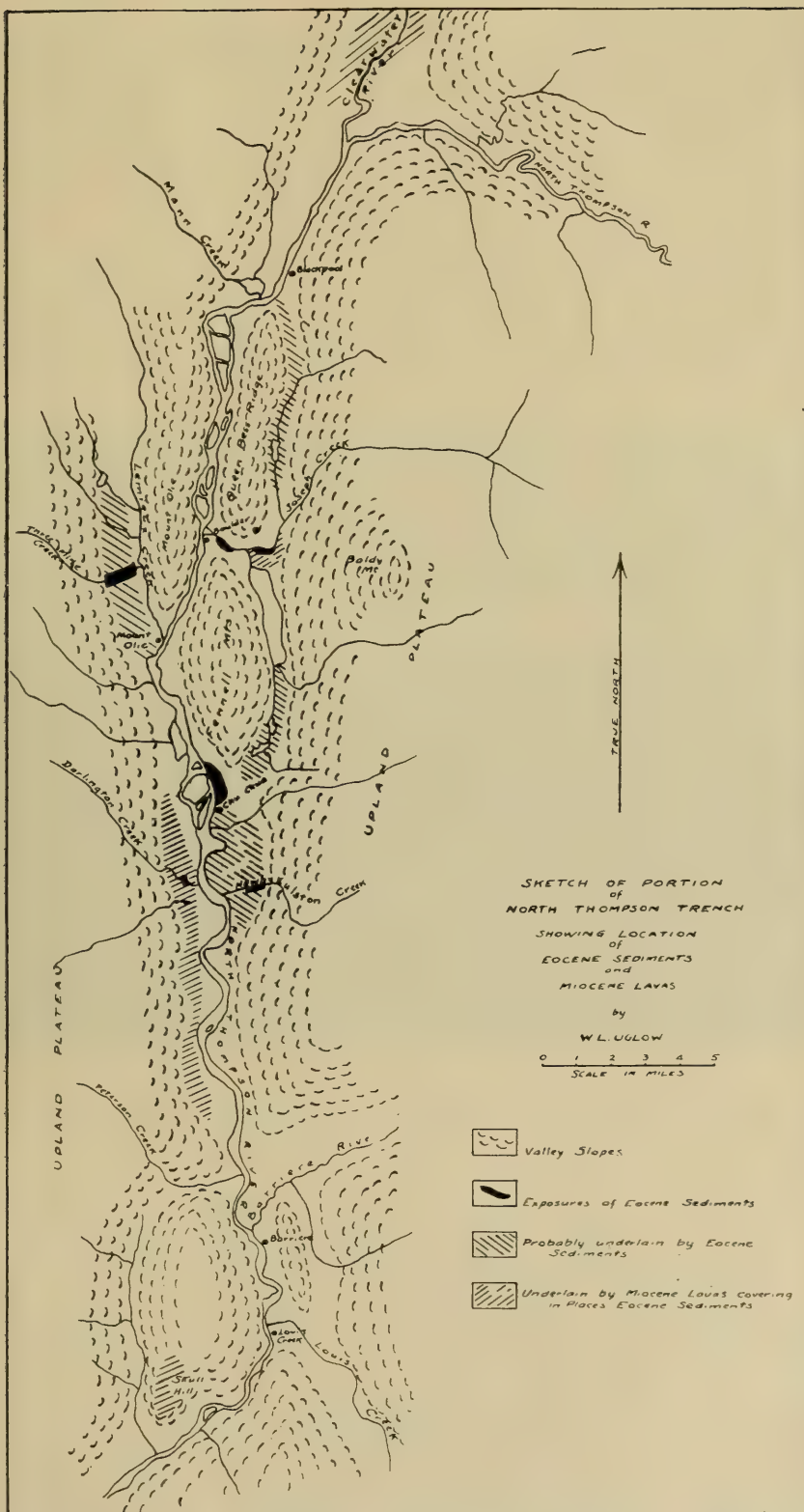


FIGURE 2.—*Sketch Map of Portion of North Thompson Trench*
Showing location of Eocene sediments and Miocene lavas.

ridges, constituting foothills to the main valley slopes, on either side of the river. In all of the exposures the formation strikes parallel to the trend of that part of the trench in which it lies, but in each case the beds dip 20 to 25 degrees toward the eastern side of the trench. No complete stratigraphic section is exposed from which the thickness of the formation could be determined. The limited evidence which is available, however, points to a thickness of at least 2,000 feet.

Andesitic and basaltic lavas of Miocene age occur in the lower portions of the valley, chiefly below the 2,500-foot contour. On Skull Hill, in the vicinity of Louis Creek, the lavas are found between elevations of



FIGURE 3.—*North Thompson Trench from Skull Hill*

The view was taken looking south down the trench and shows the side slopes of the present valley and portion of upland plateau.

2,000 and 3,000 feet, producing a flat, mesa-like top. The erosion remnants of these rocks may be seen as rock-defended terraces along both sides of the valley, in many places overlying the sediments of the Chu Chua formation. The separate flows are nearly horizontal, but locally show dips up to 20 degrees.

POST-TERTIARY ROCKS

These are of three types: (1) the glacial drift and erratics which mantle the gently undulating uplands beyond the rim of the trench; (2) the glacio-fluvial and Recent gravels, sands, and silts are now carved

into a series of flats and terraces clinging to the sides of the main valley and its tributaries to a height of 1,000 feet above the bottom, and (3) Recent lava flows of small ascertained extent, covering some of the Recent valley fill in U-shaped glacial tributary trenches.

CRETACEOUS PENEPLAIN

When one views the topography in the vicinity of the trench from an altitude of 4,000 or 4,500 feet, he is struck by the fact that he is standing on a gently undulating elevated plain, into which the North Thomp-



FIGURE 4.—*North Thompson River at Chu Chua*

The view was taken looking east across the river. The foothills on the east side of the river are underlain by early Eocene sediments.

son and its tributary streams have incised deep youthful channels. From such an elevated point in the vicinity of Chu Chua, for example, a view down the valley to the south reveals four important physiographic features: (1) a dissected upland plain, (2) several steep rocky monadnocks, (3) the deep youthful valleys, and (4) a very broad, shallow, elongated depression of the upland surface, paralleling the course of the North Thompson Valley, intermediate in position between the top of the present river valley and the general level of the undulating plain. This depression varies from 15 to 25 miles in width, and its axis lies along the course of the present North Thompson River. It represents the

valley of the ancestor of the present river as it flowed with a very low gradient, bounded by relatively flat valley slopes, over the peneplain, characterized by physiographic old age. The peneplain is early Eocene or pre-Eocene (probably late Cretaceous) in age, and the depression is the valley of the pre-Eocene (probably Cretaceous) North Thompson River.

EARLY EOCENE UPLIFT

This peneplain was slowly uplifted in pre-Middle Eocene time. Since Eocene sediments occur in the trench at a depth of 3,000 feet below the upland, the uplift must have been approximately of that magnitude. It was of sufficiently slow development to allow the river to maintain throughout the course it had previously carved out for itself and to cut its present trench beneath its former peneplain valley. The initiation of the uplift can not be definitely dated, but it was sufficiently pre-Middle Eocene to allow the river to cut down through 3,000 feet of hard pre-Tertiary rock formations. A slow rejuvenation of the river accompanied the progressive uplift, and by the time of the commencement of sedimentation, in Middle Eocene, the river had entrenched itself to a depth of about 3,000 feet. The uplift was completed when sedimentation began, or by the middle of the Eocene.

It is probable that this early Eocene uplift represented the Laramide revolution as it affected the southern interior of the province. If so, the Laramide revolution was one of slow progress which commenced in late Cretaceous or very early Tertiary time and was completed before the end of the Eocene.

MIDDLE TO UPPER EOCENE SEDIMENTATION

The Chu Chua formation preserves a fragmentary record of the topography and geology of the trench bottom after it had been cut in Middle to Upper Eocene times. As stated above, this formation consists of a basal conglomerate varying in thickness up to 200 feet, evenly bedded, highly feldspathic arkose, sandy shale, intraformational conglomerate, and seams of coal.

The lithology, stratigraphy, and structure of the upper part of the formation indicate that it was deposited under conditions of still or very sluggish water. The basal conglomerate is a tumultuous deposit characterized by a heterogeneous mixture of large and small angular fragments of the greenstone which is the adjacent country rock, interspersed

with heavy stream wash, consisting of subangular to rounded fragments of granite and granodiorite, rocks which intrude the greenstone at a distance of 1 to 2 miles back from the trench. This conglomerate represents alluvial fan or cone deposition from tributary valleys. The overlying arkose and shale, which are characteristically thinly bedded and lack cross-bedding, are the products of deposition in quiet waters, with very little or no current. The coal seams represent stages in the valley filling when back sloughs and lakes were prominent, in which large areas of the valley fill were at the level of the water and were covered with a thick growth of evergreen and deciduous trees. Spasmodic recurrences of this condition and periodic downfaulting of the basin would account for the accumulation of upwards of 2,000 feet of sediments, in which are interstratified at least fourteen seams of coal.

From the shales of the Chu Chua formation the writer collected several suites of plant fossils, which were submitted to Prof. Edward W. Berry, of Johns Hopkins University, for determination. Professor Berry places them definitely in the Middle or Upper Eocene.⁴ The Chu Chua formation, therefore, constitutes the first discovery of definitely established Eocene sediments in the southern interior of British Columbia. Dawson,⁵ Daly,⁶ Mackenzie,⁷ Drysdale,⁸ and others report the occurrence of similar groups of rocks, but they have been placed in the Oligocene or loosely connected with some part of the early Tertiary record.

OLIGOCENE DIASTROPHISM AND EROSION

BLOCK-FAULTING

Following a partial consolidation of the Eocene sediments, the formation was block-faulted probably during the Oligocene, along lines running in northeasterly directions, parallel to the trend of the valley. As a result of this faulting the rocks of the series are now found as strike ridges on both sides of the trench, but dipping uniformly at 20 to 40 degrees toward the east. In other words, they dip away from the valley side and into the trench on the west side of the river, and away from the trench and into the valley side on the east side of the river.

This diastrophism caused the rejuvenation of the river. Erosion by the river then beveled the upturned edges of the sedimentary series.

⁴ Summary Rept., Geol. Surv. Canada, part A, 1921, pp. 85-86.

⁵ Ann. Rept. Geol. Surv. Canada, 1894, pp. 66-76 B.

⁶ Geol. Surv. Canada, Mem. 38, part 1, pp. 86-88.

⁷ Geol. Surv. Canada, Mem. 87, pp. 31-39.

⁸ Summary Rept., Geol. Surv. Canada, 1912, pp. 140-144.

Owing to the absence of continuous exposures, the extent and depth of this erosion can not be estimated.

This block-faulting may possibly be correlated with that period of tension which followed the compressive stresses of the Laramide revolution. Daly⁶ and Mackenzie⁷ found similar faulting of the early Tertiary measures along the international boundary and in the Flathead Valley in southern Alberta. It is probable that these crustal movements are all of the same age, and in the North Thompson basin they can be definitely placed between the end of the Eocene and the period of Miocene vulcanism.

In reference to the deformation of the peneplain as a result of the Oligocene block-faulting, it may be noted that the western side of the trench is much lower than the eastern; and this may be due to the combined effects of the Oligocene and post-Miocene diastrophism.

MIOCENE VULCANISM

During the Miocene period extensive subaerial floods of andesitic and basaltic lava poured out over the southern interior of the province. Within the region in question these flows were mostly hornblende- and augite-andesite, usually highly scoriaceous and amygdaloidal. Agate, hyalite, zeolites, and native copper are found as fillings of the amygdules. The lavas flooded the valleys and depressions and covered the upturned and eroded measures of Eocene age. In the valley of the Clearwater River, a southerly flowing tributary of the North Thompson, great terraces of this lava still remain as remnants from post-Miocene erosion, and underneath the lava may be seen cliffs of bleached and kaolinized granite, the result of pre-Miocene weathering.

POST-MIOCENE DIASTROPHISM AND EROSION

Further faulting within the trench followed the extrusion and solidification of the lavas. Along a fault zone running north and south through the center of the trench, the western wall of the valley was down-faulted with respect to the eastern wall. This faulting was accompanied by the production in the lava of closely spaced shearing planes parallel to the strike of the main fault. Owing to the displacement, the flows which overlie the Eocene sediments on the west side of the river are now at the same level as the coal measures of the Eocene on the east bank. The vertical displacement along this fault was at least 600 feet and probably as much as 1,000 feet. Evidence of this faulting is still preserved in

the difference of elevation of the upland on the east and west sides of the trench.

Erosion, accompanying and following the diastrophism, succeeded in removing a large part of the lava cap and underlying Eocene sediments from the valley. The only portions of the Miocene lavas which remained at the end of the Pliocene consisted of rock terraces rising to heights of 800 feet above the bottom of the valley. The central portion of the trench was reexcavated to a depth about equal to that which obtained at the inception of Eocene sedimentation.

PLEISTOCENE GLACIATION AND SUBSIDENCE

A Pleistocene ice-cap which filled the valley and extended to a height sufficient to glacialize and groove rock hills at an altitude of 7,500 feet covered the southern interior and flowed in a general southeasterly direction. The ice removed the weathered rock from the ridges, deposited erratics and till, and produced a "roche moutonnée" effect on the rocky slopes of the valley and intratrench ridges (Mount Olie, Queen Bess Ridge, Fennell Mountains). It supplied to the glacial river great quantities of boulders, sand, silt, and mud, which were deposited lower down as a thick valley fill. Thick deposits of white silt (the "White Silts" of Dawson⁹) were deposited at this time, covering the glacio-fluvial gravels. Remnants of these may now be seen as terraces up to altitudes of 2,250 feet along the sides of the North Thompson Valley. The presence of these silts on top of the glacio-fluvial gravels indicates a submergence of the land surface, probably below sealevel.

RECENT UPLIFT, EROSION, AND VULCANISM

Following the period of the deposition of the "White Silts" there was a considerable uplift of the southern interior, which caused a rejuvenation of the streams. The North Thompson Valley was reexcavated in the unconsolidated Pleistocene sediments, and the "White Silts" and glacio-fluvial deposits were carved into a series of finely developed hanging terraces. The eroded portions of the unconsolidated formations were reassorted in Recent times and are now found constituting the lower benches and river flats, which are such marked features of the valley bottom. As a result of this post-Pleistocene or Recent erosion, the North Thompson Valley was again deepened so that its bottom is now in a great many places at approximately the same stratigraphical depth as it was in Middle Eocene and Pliocene times.

⁹ Ann. Rept., Geol. Surv. Canada, vol. vii, 1894, pp. 283-291 B.

In the postglacial gorge of Mann or Blackwater Creek, two 10-foot flows of basic lava cover Pleistocene or Recent unconsolidated stream gravels. These flows point to a recurrence of volcanic extrusion in Recent times.

GLACIAL DRAINAGE ON THE COLUMBIA PLATEAU¹

BY J. HARLEN BRETZ

(Presented before the Society December 30, 1923)

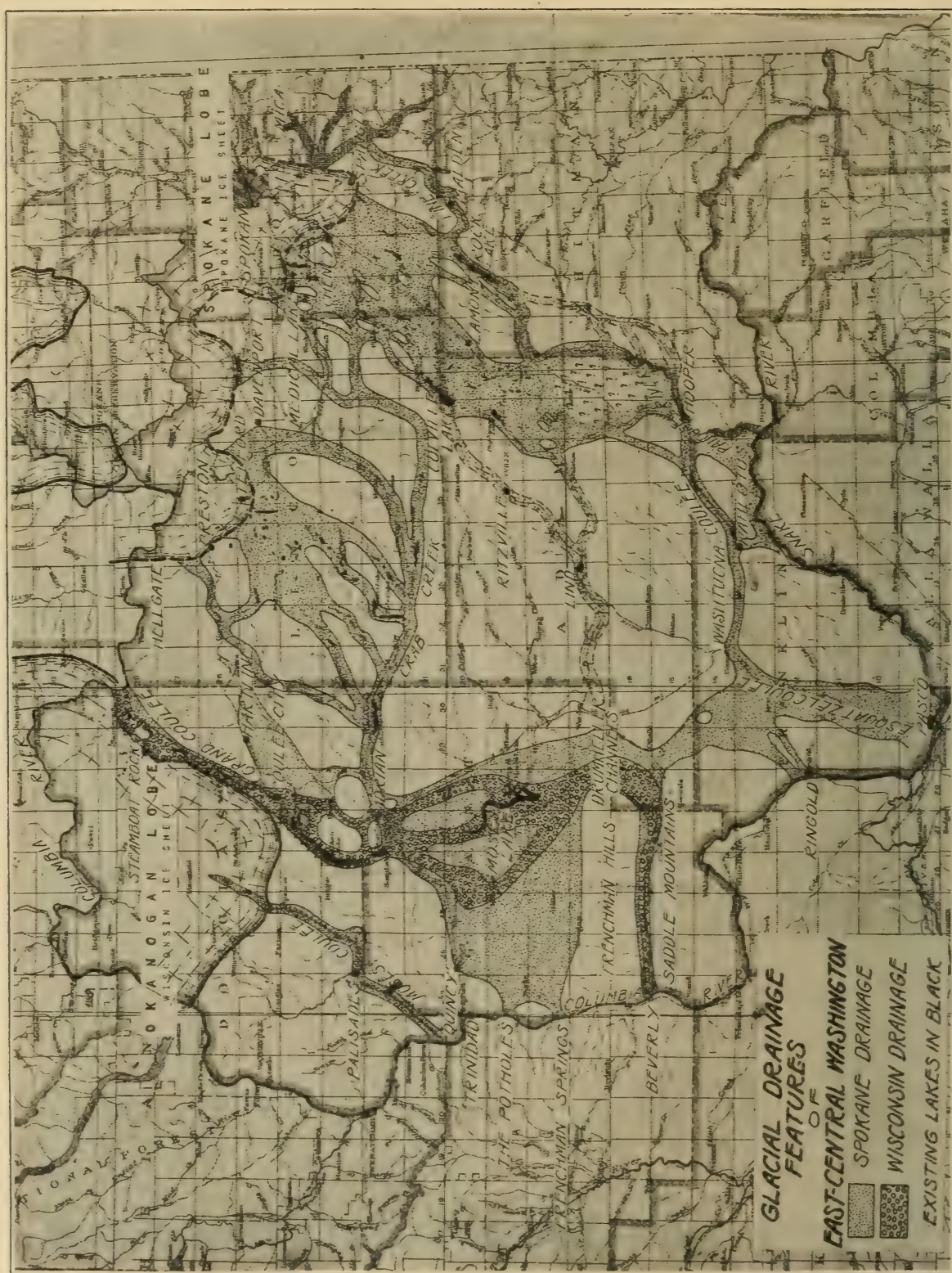
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INTRODUCTION

Only the northern part of the Columbia Plateau is concerned in this study and only waters from the Cordilleran ice-sheet. Two glacial epochs are involved—one the Wisconsin, the other as yet undated. Besides contributing to the geological history of the region, this article endeavors to show that glacier-born streams, under proper conditions, are erosive agents of great vigor over large tracts far from the front of the melting ice.

¹ Manuscript received by the Secretary of the Society January 10, 1923.



TOPOGRAPHY AND DRAINAGE

The Columbia basalt plateau is separated from several mountain ranges on the north and from the Cascade Range on the west by the trench in which flows Columbia River. On the east, the plateau abuts against and interfingers with the Cœur d'Alene Mountains of Idaho. When the Miocene basalt flows of this region ceased, the lava plain abutted in a similar fashion against the mountains on the north and west. The cutting of the Columbia Valley between mountains and plain in the great arc known as the "Big Bend" has partially isolated this portion of the former lava plain and thus given it the character of a plateau. The Columbia Valley north of the plateau is a great canyon, 1,500 to 2,000 feet deep, its bottom less than 1,000 feet above the sea. It does not, however, serve for the complete northern boundary of the plateau. Spokane River, its tributary from the Cœur d'Alene Mountains on the east, may be considered as marking the northern limit of the plateau east of the Columbia in Washington. The canyon of Snake River in Washington marks the southern margin of that portion of the plateau with which this study is concerned.

Widespread, gentle warping of the Columbia basalt flows in Washington has made a great shallow, structural basin, the rim of which is roughly the margin of the plateau on the west, north, and east. The flows, originally horizontal, are 2,500 feet above tide about the eastern and northern margins and 4,000 to 6,000 feet above tide in the Cascade Range, along the western margin. The lowest tract in the basin is the general vicinity of the junction of Columbia and Snake rivers. Here the basalt flows dip below the Columbia, perhaps below sealevel. Drainage escapes to the Pacific through the Columbia Gorge, cut in the Cascade Range, the greatest water gap on the North American continent.

The expression "the plateau" will be understood in this paper to denote that portion of the Columbia Plateau bounded by Spokane, Columbia, and Snake rivers and the mountains of Idaho.

There are many lesser basins of structural origin in the great feature above outlined and many sharp flexures, particularly in the western part, near the youthful Cascade Range. Most of the drainage lines of the plateau are consequent on its warped surface. The Columbia is the great exception. It approaches the rim from the north, but, instead of crossing and entering the basin, it swings westward and then southward in the Big Bend already described, before entering the basin. As a consequence of this, no waterway of importance enters the Columbia from the concave side of the Big Bend. Drainage of the plateau is centripetal,

and the master stream finally enters the basin after it has skirted the northern and western sides in part. Only after it enters does it receive the drainage of the plateau.

The northern rim of the plateau is the highest part. It is a broad divide extending from Spokane west to the southward bend of Columbia River at the foot of the Cascade Range, parallel to Spokane and Columbia rivers and on the average only 10 miles south of them. Down its southern slope flow numerous tributaries to Palouse River and Crab Creek. These two stream systems and Moses Coulee, farther west, are intimately concerned in the glacial drainage history to be outlined.

Palouse River is the largest stream on the plateau north of Snake River. Its drainage area lies in the southeastern quarter of the plateau. Its system consists of a large number of minor centripetal streams which flow westward toward the central part of the basin. It enters Snake River in the middle of the plateau's southern margin. Crab Creek gathers the small centripetal streams from the north-central part and carries their discharge westward toward the Columbia, which it enters not far south of the middle of the western margin of the plateau.

Crab Creek has the largest drainage area of any stream on the basalt plateau of Washington, but there is so little rainfall and so much evaporation in this area that no water today flows to the Columbia. It has been otherwise in the past. The area possesses a complete system of streamways. Some of them are normal valleys in maturity, only the rainfall in some more humid times of the past having formed the streams. Others are canyons of noteworthy, even spectacular, depths, intimately related to the history of the glacial drainage of the plateau.

STRATIGRAPHY

The dominant formation of the plateau is the Columbia lava. It has been completely covered by sedimentary deposits of silt, ash, and loess. These have suffered much from glacial and fluvial erosion, but still persist and give character to the topography and soils of more than half of the plateau. In the western part of the plateau this sediment is presumably the Ellensburg formation. It is intimately related to the basalt, its deposition beginning in some places before the great basalt flows had ceased, and in other places later and minor basalt flows occurring after its accumulation had well begun. If the sedimentary formation, or its lower part, is Ellensburg, its presence indicates clearly that the plateau is determined by the original surface of the Miocene lavas, not by any later erosional plans developed on the basalt.

PHYSIOGRAPHY

The surface of the plateau bears two strikingly different physiographic aspects. Locally, one is known as "Palouse Hills" and the other as "Scabland." Not alone are these sharply contrasted areas in close juxtaposition, but they are interfingered and interlocked. Every one of the seven counties of the plateau possesses areas of both types.

The "Palouse Hills" topography is best shown in Whitman County south of Spokane and in the eastern half of the Palouse River system. The region is essentially all in slopes, a network of drainage lines covers it, the soils are fine and deep, and ledges of basalt are exposed only on



FIGURE 2.—*Steptoe Butte and the maturely dissected Palouse Region east of the "Scablands"*

lower slopes and rarely on these. Profiles are convex only on hilltops; all valley slopes are strikingly concave. The "Palouse Hills" topography is typically mature. It is developed in the super-basalt sedimentary in large part. Its relief averages about 250 feet. The main streams now are in canyons in basalt below the floors of the mature valleys. This type of topography (figure 2), with the same soils and underlying formation, is widely distributed elsewhere on the plateau, but the drainage pattern is not so intricately detailed farther west, where rainfall since the uplift of the Cascade Range has been less.

The "Scablands" are lowlands among the groups of "Palouse Hills," plane in a general way, but diversified by a multiplicity of irregular and

commonly anastomosing channels and rock-basins eroded in basalt, and containing meadows, swamps, and lakes (figures 3 and 4). The local name refers to the absence of soil over much of these tracts, the basalt outcropping in ledges and over considerable level areas. The "Scab-



FIGURE 3.—*Channeled "Scabland" of Spokane Age*

This area is on the plateau near the head of Grand Coulee.

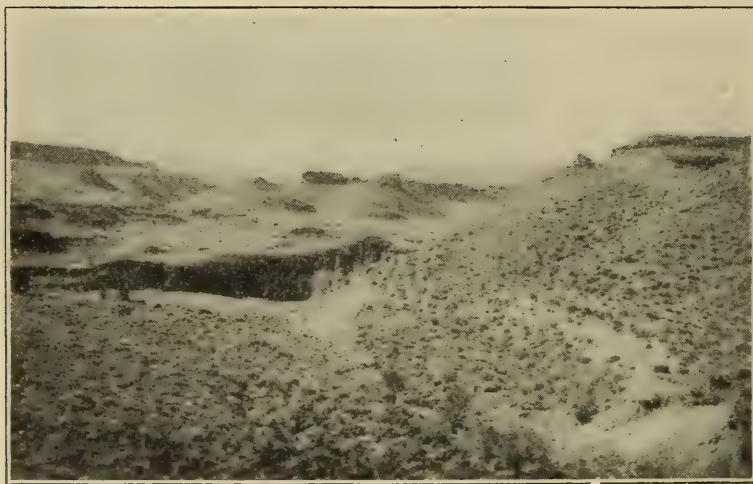


FIGURE 4.—*Spokane Drainage Channels in Mid-length of Moses Coulee*

The narrow inner channel is of Wisconsin age.

lands" are commonly elongated tracts, with their channels and rock basins elongated in parallelism. Some of these channels are canyons several hundred feet deep. Almost all of the lakes of the plateau lie in the Scablands (figure 5). None occur in the Palouse Hills.

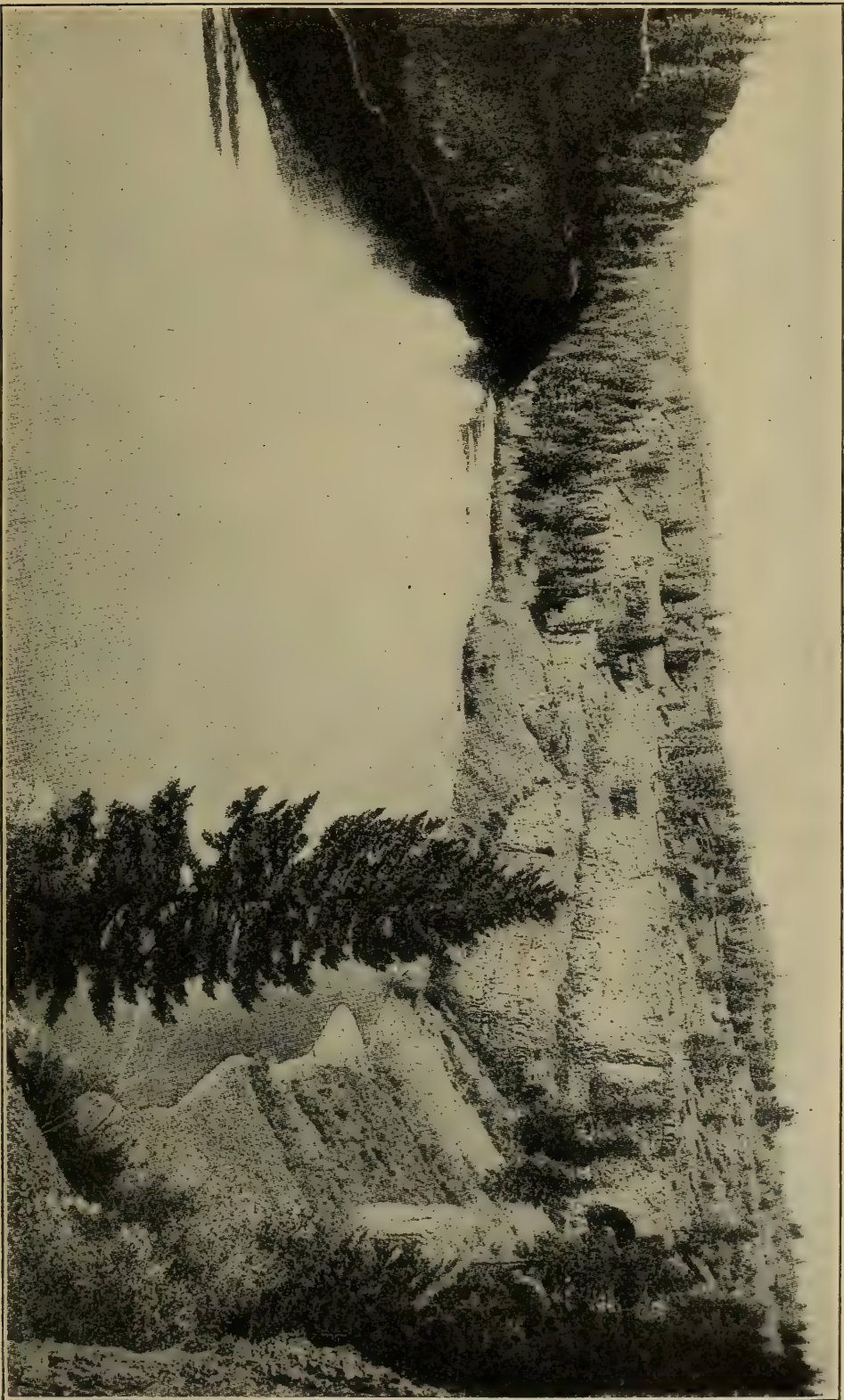


FIGURE 5.—*Rock Lake, in a glacial Drainage Channel of Spokane Age*

GLACIATION

Probably the entire highland area north of the plateau was buried beneath the Cordilleran ice-sheet during the Pleistocene glaciations. At least three times the Cordilleran ice forced a crossing of the Columbia Valley and advanced onto the plateau. The latest of these, of Wisconsin age, has been described; the earlier ones thus far have been but noted in the literature. Farther east, where Spokane River serves as the boundary, only two glacial invasions of the plateau are known, both of which are pre-Wisconsin, and only brief notes exist regarding them.² The latter of these two glaciations is well recorded in the topography. With it and the Wisconsin glaciation on the northwestern part of the plateau this paper chiefly deals.

THE SPOKANE GLACIATION

GENERAL STATEMENT

Observers for years have been noting the existence of granite boulders scattered over the basalt plateau of Washington far beyond the limits reached by the Wisconsin ice. They are now known to belong to four categories: (1) derived from knobs of granite buried in or projecting above the basalt flows, (2) berg-drifted in a widespread ponding during late Wisconsin time,³ (3) glacier-borne during glaciations earlier and more extensive than the Wisconsin, and (4) berg-carried in great streams born of one of these earlier ice-sheets.

The precise limits reached by the earlier ice-sheets are as yet unmapped, but enough is known to indicate that the latter of the two crossed the Columbia and Spokane valleys from the northern highlands, pushed well up on the rim of the plateau, and in the vicinity of Spokane advanced south of the rim divide as far as Spangle and nearly to Cheney. No prominent morainal margin now exists, if one ever was formed, but the till, the striated erratic boulders, the deposits of outwash material, and the drainage channels constitute adequate evidence of the glaciation. It is here named the Spokane glaciation. Details which are essential to a conception of the character of the Spokane glaciation, so far as it is now known, are here presented.

² Frank Leverett: *Bull. Geol. Soc. Am.*, vol. 28, 1917, p. 143.

M. M. Leighton: *Bull. 22, Wash. Geol. Survey*, 1919.

Thomas Large: *Science*, vol. 56, 1922, p. 335.

J. T. Pardee: *Science*, vol. 56, 1922, p. 686.

³ J. H. Bretz: The late Pleistocene submergence in the Columbia Valley of Oregon and Washington. *Jour. Geol.*, vol. 27, 1919, pp. 489-506.

SPOKANE RIVER AND PALOUSE RIVER DRAINAGE

Vicinity of Spokane.—The city of Spokane is built in a valley eroded in the basalt, not more than 10 or 15 miles from the margin of the plateau. To the east rise the mountains of Idaho—an older, higher land surface whose embayed and spurred flanks make an irregular contact between mountains and plateau. Moran Peak, about 8 miles southeast of Spokane, is one of many isolated peaks of the older mountains, standing out in the plateau. Remnants of the plateau extend perhaps 20 miles north of Spokane, separated by the valleys of the Spokane and its tributaries and terminated on the east and north by higher hills of crystalline rock. These remnants constitute mesas, such as Pleasant Prairie and Five-Mile Prairie, about 2,400 feet above tide and about 400 feet above the surface of the Wisconsin valley trains in the intervening valleys. The summits of these flat-topped hills apparently mark essentially the original surface of the Columbia lava flows. West and south of Spokane the Columbia plateau extends for many miles, interrupted only here and there, near the margins, by island-like hills or mountains of older rock.⁴

Boulders of various crystalline rocks, igneous and metamorphic, with characteristic glacially planed, beveled, and striated surfaces, lie scattered on the surface of the Columbia plateau about Spokane, extending as far south as the base of Moran Peak and the village of Spangle, close to the base of the Palouse Hills. They have not been found, however, in this maturely dissected country, nor at altitudes much above 2,500 feet above tide on the northern slopes of Moran Peak and Mica Peak, east to the Idaho line.

Outwash gravel deposits⁴ at similar elevations and close to the driftless Palouse Hills are known at Pantops, along the Inland Empire Highway, and elsewhere. The deposit at Pantops is at least 30 feet deep and possesses current bedding with southward dip. It lies on the basalt plateau not more than a mile west of the base of Moran Peak, at an altitude close to 2,400 feet above tide. The gravel in the deposit is not stained or cemented; it looks as fresh as Wisconsin gravel in the Great Lakes region. Scattered through it are hundreds of granite boulders averaging 3 feet in diameter, many of them exceeding 10 feet. The gravel is not coarse, there are no cobble phases in it, and the boulders are wholly out of accord with the gravel as a stream deposit. Furthermore, the boulders are subangular and show considerable decomposition of the granite on their less-rubbed surfaces. They doubtless are a local contribution, de-

⁴ Named "steptoes" by Russell.



FIGURE 6.—Glacial Ice and Drainage near Spangle, Washington

rived by glacial plucking of the decayed granite on the northern flanks of Moran Peak and Mica Peak. They are boulders of decomposition and doubtless were easily quarried by the ice. Their abundance in the gravel and the little rubbed condition are clear indications that the front of the ice-sheet did not advance far beyond this place.

Despite the fresh appearance of the gravel at Pantops, the topography gives no clue to its presence. From what can be seen now, it is difficult to determine whether the Pantops gravel is a kamey deposit or is a remnant of a valley train or outwash plain. It blends into the lower slopes of Moran Peak and the basalt plateau.

There are other gravel deposits on the plateau immediately south of Spokane, similar to that at Pantops in altitude, bedding, freshness of material, and absence of fluvio-glacial forms, but none possess the granitic boulders of decomposition.

Vicinity of Spangle.—The village of Spangle is 12 miles almost directly south of Pantops and 15 miles south of the eastern part of Spokane. Maturely dissected driftless country lies to the east and south, a scabland plain to the west (figure 6). Striated erratics have been found here as high as 2,500 feet above tide, on the slopes which face the scabland, and within 100 feet of the hill tops.

The drainage of this part of the Palouse country is northwestward, toward the scabland tract. When glacial ice stood at the limit marked approximately by the north-south line between Pantops and Spangle, this drainage was blocked and a lake was formed for which another dischargeway was necessary. The waters of Latah (Hangman) Creek and its tributaries, Rock Creek, California Creek, Mica Creek, etcetera, augmented by a great volume of water from the ice, spilled over the divide west of Latah Creek, about 6 miles southeast of Spangle, and entered North Pine Creek, a minor tributary of Pine Creek, flowing thence southwestward 20 miles across the unglaciated Palouse hill land to enter the scabland region at the north end of Rock Lake. The prominent spillways were eroded across the divide into North Pine Creek Valley.⁵ The floor of each of the cols is on basalt at about 2,450 feet above tide *and is essentially a scabland tract*. The glacial waters back of this double spillway doubtless were ponded in Latah and Rock Creek valleys.

During the occupation of the spillways these waters eroded deeply in the basalt. The larger spillway is half a mile wide at the col. Both are well shown on the Oakesdale topographic map and on the Spokane County soil map. Near the junction of North Pine Creek and Pine

⁵ Thomas Large: The glaciation of the Cordilleran region. *Science*, vol. 56, no. 1447, 1922, p. 335.

Creek and in the larger valley are great bars and terraces of coarse basaltic gravel, poorly sorted and much of it subangular. Mingled with it are a few cobbles and small boulders of granite and quartzite. The material farther down Pine Creek Valley is finer and better sorted. It seems clear that most of the debris was derived by erosion of the spillways themselves, only a small amount of foreign material crossing the lake on ice-rafts from the front of the ice-sheet.

The valley during this episode in its history was but a channel. The glacial stream filled it from side to side for a depth of tens of feet. This is shown a few miles above Malden, where the stream flooded over a low shoulder of basalt, cutting a channel in the rock at least 40 feet deep, though the main valley alongside was wide open and received gravel deposits. North Pine Creek now flows through this channel. The main current of the stream here cut across a curve in the preexisting valley. The gradient of this glacial stream was close to 30 feet to the mile in its upper part and about 20 feet to the mile in the lower part.

The character of the terraces in Pine Creek Valley below the junction of North Pine Creek is instructive. Like the Pantops deposit, there are no well defined depositional forms. The terrace tops do not abut sharply against the hillslopes, but instead waste has crept out on the gravel deposits from the slopes above, and the valleyward edges of the terraces have become rounded and notched by widened gullies until the terrace form is obscure. This is well shown at Kenova, where the Chicago, Milwaukee and Saint Paul Railroad has opened a large pit in the gravel. Furthermore, these terraces are only fragments here and there of what was once a continuous filling. Despite these evidences of considerable age, the material in the deposits appears fresh. It is unstained and uncemented.

Only one other glacial drainage route across the mature Palouse country is known, and this was but a tributary to the Pine Creek channel. Waters from glacial ice spilled southward through a low place at Mica between Moran Peak on the west and Mica Peak on the east. The altitude of the col at Mica is hardly 10 feet above that southeast of Spangle. Pounded waters of the Latah Valley must have backed up almost to the village of Mica. Whether or not a considerable lake lay to the north of the Mica col,⁶ it is certain that the ice-sheet was hard against the northern flank of Moran Peak and its drainage probably passed through a settling basin before entering the short Mica channel. A few erratics, one of them striated, have been found in the channel, but no glacial

⁶ "Lake Spokane" of Large.

stream gravel. Nor was the Mica channel eroded to any extent. Probably ponded waters were backed up from the south until the last stages in erosion of the North Pine Creek channel.

Vicinity of Cheney.—Cheney lies 15 miles southwest of Spokane and 10 miles northwest of Spangle. About this town are recognizable the same elements in the topography as already outlined—the higher pre-basalt hills, the Palouse type of maturely dissected hills, and the lower scablands. The scablands have less relief than either of the other elements, but are much rougher. They are commonly a maze of minor channels and depressions eroded in the basalt.

Cheney lies at the head of the largest tract of scabland on the plateau—a tract which extends from Spokane River to Snake River. It is not uninterruptedly scabland, however. It contains isolated groups of Palouse Hills. One of the largest of these groups lies immediately north of Cheney and has an area of about 13 square miles. Many of them are not a square mile in area. In topography and in soil, these tracts are identical with the Palouse wheat country to the east and southeast; but the gentle, concave lower slopes of maturity, so characteristic of these hills, is absent on the peripheries of the isolated groups. Instead, these outer slopes are much steeper and are generally convex. They meet the roughened plain of the scabland with a definite angle. The bounding slopes clearly are much younger than the valley slopes among the hills.

The hill groups are elongated northeast-southwest, in harmony with the elongation of the channels on the basalt surface and with the scabland tract as a whole. In many of these linear groups there are longitudinal valleys, not of the mature type, but with steep sides and scabland floor. All such valleys pass completely through a hill group, leading from the rocky plain into the rolling hills and out again to the plain.

Another feature of this great scabland tract is the presence of many widely scattered granite boulders. Nowhere (with one exception, to be detailed later) has this foreign debris been found back among or on the slopes of the hill groups. Associated with it, but much less common, are terraces of gravel composed largely of basaltic debris, but with granite and other foreign material distributed through it. Such deposits commonly lie on the southwest sides of rocky shoulders or hills in the channels. They have been opened for railroad ballast and road metal at many places over the whole scabland area.

From a survey of the patches and groups of the Palouse Hills scattered over the scabland plain south of Cheney, it seems clear that they are but remnants of a once continuous cover of the basalt, and that the scablands have resulted from removal of the Palouse Hills by erosion in

some unusual way. The basalt of the scablands is the firm and resistant foundation on which the hills stand. The overlying sedimentary deposit is the formation whose etched surface constitutes the hills.

The scabland does not extend north of the Palouse Hills about Cheney and Medical Lake, though it does extend among them in great river channels to their northern limits. Farther north, there is neither scabland nor Palouse Hills. The area is a basalt plain with widely spaced mature valleys and broad, low, flat divides. The whole is thinly covered with glacial drift, some of it a stony till with hummocky morainic topography, some of it washed and stratified glacial sand and gravel. The ice-sheet clearly covered this plain. It, however, did not extend southward into the scabland area, except for a minor lobe between Moran Peak and the Cheney Hills, which reached as far south as Spangle. The association of broad undissected divides with shallow, mature valleys, all in resistant rock (for example, Deep Creek and its tributaries) is anomalous. It is believed to be the result of the glaciation of a tract which possessed a typical Palouse mature topography, developed largely in a silt or ash deposit, but etched in the deeper valleys into the surface of the underlying basalt. The ice removed every trace of the hills in the weaker formation, bringing the whole down to the surface of the basalt; in effect, it cut off the hills well down to their bases without greatly modifying the main valley bottoms.

Vicinity of Lamont.—Twenty miles to the southwest of Cheney the escaping glacial waters had become largely concentrated between Sprague and Lamont. The eroded tract here is nearly 10 miles wide and without a surviving Palouse hill. A sheet of torrential water must have spread completely across the scabland between these two towns. It rapidly removed the weaker material of the Palouse Hills and then scoured out channels in the basalt. By the close of its occupancy it had concentrated in certain channels and eroded them approximately 100 feet below the surface of the basalt. Colville (Sprague) Lake lies in one of these channels.

Between Lamont and Rock Lake, to the east, is a linear tract of Palouse Hills about eight miles wide and traversed by but one valley possessing bare rock in its floor and scattered granite fragments. Separating this tract from the Palouse country of Whitman County is a great river channel, occupied now by Rock Creek and several elongated lakes. Rock Lake is the largest of these and, save one, is the largest and longest lake on the Columbia Plateau of Washington. Rock Lake (see figure 5) is bounded on both sides by sheer cliffs of basalt 200 feet and more in height. There is no damming of consequence in the channel at the lower

end of the lake. Rock Lake exists because the ancient river here excavated more deeply in its bed than it did a little farther down stream. Rock Lake is typical of most lake basins of the Columbia Plateau in Washington, in that it is a much elongated true rock-basin in an ancient river channel in a scabland area. The only part played by glacial ice in the formation of these basins is that of supplying the stream. Factors essential for development of these rock-basins made by streams are (1) large volume abruptly introduced, (2) high gradient, and (3) rock which is closely and vertically jointed. The excavation was accomplished by plucking, rather than by grinding.

Vicinity of Kahlotus.—About 25 miles south of the latitude of Rock Lake the scabland is more restricted. So far as now known, all channels but one entered Snake River in the vicinity of the present junction of the Palouse. The one channel which escaped the control of the Palouse system is traceable westward, by way of Washtucna, through Kahlotus, to Esquatzel Coulee at Connell. It is a splendid abandoned channel, in places 250 to 300 feet deep. Throughout its length it has all the characters of the channels of the scabland tract to the east and northeast except that it does not lie in such a tract. It probably was sufficiently deep at the inception of the flood to contain the waters which came its way. A few miles above the junction of Washtucna Coulee, Esquatzel Coulee has none of these characters, but possesses the broad, graded slopes of maturity.

Vicinity of Sprague.—The westernmost channels among the Palouse Hills near Cheney which discharged to the Palouse system enter the broad scabland between Sprague and Fishtrap. The roughness of these channel floors, due to the gashed basalt, is in striking contrast with the smooth flowing contours of the inclosing hills. One needs but little imagination to see again from these hilltops the torrents of glacial waters invading from the north and following the lower valleys southward to join the scabland between Sprague and Lamont. These hills, like those in the Palouse wheat lands, are composed largely of a fine-textured unindurated sediment, probably of lacustrine origin.⁷

It does not seem probable that any water, other than that which occupied Washtucna Coulee, escaped westward from the Palouse drainage during the Spokane epoch. There are two possible routes, however, of such discharge, namely, one by way of Keystone, near the lower end of Colville (Sprague) Lake and Ritzville; the other by way of Ralston. Both enter Lind Coulee at Lind. The altitude at the head of the Ritz-

⁷ M. R. Campbell: Guidebook of the Western United States. Part A: The Northern Pacific Route. U. S. Geol. Survey, Bull. 611, 1915, p. 163.

ville route is 53 feet above the surface of Colville Lake in the adjacent scabland, and Ralston is not 100 feet above the floor of the Cow Creek channel. Along both routes are deposits of stream gravel.⁸ Yet no scour of the floor by glacial waters, nor steepened valley walls, nor scattered erratic boulders or cobbles were seen.⁹ It is possible that these routes were used for but a short time early in the glacial flooding, or it may be that the gravels are older than the Spokane glaciation. It may be, also, that the gravels in channels near Winona and Lacrosse, south of Rock Lake, are of pre-Spokane age.

The scablands of the Palouse drainage, with channeled basalt, deposits of stratified gravel, and isolated linear groups of Palouse Hills, their marginal slopes steepened notably, bear abundant evidence of a great flood of glacial waters from the north. This flood was born of the Spokane ice-sheet. Its gradient was high, averaging, perhaps, 25 feet to the mile, and it swept more than 400 square miles of the region clean of the weaker material constituting the Palouse Hills. The hills which have disappeared averaged 200 feet in height, and in some places the glacial torrents eroded 100 to 200 feet into the basalt. This flood originated at several places along the ice-front. Great river channels exist among the remaining hills in the flood-swept region. The area overridden by the ice itself has lost every trace of Palouse Hills.¹⁰

CRAB CREEK DRAINAGE

General statement.—By at least ten different routes, glacial waters from the Spokane ice-sheet west of Cheney and Medical Lake converged to Crab Creek. Another discharge way, still farther west, that of Moses Coulee, found its own way to the Columbia above the entrance of Crab Creek drainage. The glacial streams tributary to Crab Creek, named from east to west, were Rock Creek (Lincoln County), the headwaters

⁸ M. M. Leighton: The road building sands and gravels of Washington. Wash. Geol. Survey, Bull. 22, 1919, pp. 104-105. Leighton clearly recognizes that the Spokane region had been glaciated (p. 246), that numerous glacial drainage courses exist on the plateau (p. 34), and that the scablands are due to erosion of the sedimentary material by escaping glacial waters (p. 279).

⁹ Campbell, *op. cit.*, also notes the absence of the granite boulders along the Northern Pacific Railroad, which follows the Ritzville route, west of the lower end of Colville Lake.

¹⁰ Explanation should here be made of certain glacial deposits which are older than the Spokane drift. In an abandoned clay pit near the Cheney Normal School is a very old clayey till first reported by Frank Leverett (Bull. Geol. Soc. Am., vol. 28, 1916, p. 143). It contains striated quartzite boulders and cobbles. One such boulder also has fine chatter-marks on it. Granite is present, but is crumbling or etched to such an extent that no ice-marked surfaces remain. This till also is exposed along roadsides south and east of Granite Lake, and striated erratics have been found back in the mature valleys of this hill group. It seems probable that the old till underlies much of these

of Crab Creek, Coal Creek, Duck Creek, Lake Creek, an unnamed creek west of Lake Creek, Connawai Creek, Wilson Creek, Spring Coulee, and Grand Coulee. The first eight originated from the ice on the northern rim of the plateau between Hellgate and Medical Lake. The other two entered the plateau from the Columbia Valley by one route, upper Grand Coulee, and separated at Coulee City. The location of the edge of the Spokane ice near the head of Grand Coulee is as yet unknown.

The glacial river courses are all youthful canyons in basalt. They are quite unlike the associated drainage lines of comparable length which never received glacial waters and which are typical valleys in maturity. The youthful canyons, however, were not eroded by the streams which occupy them. Despite their size, most of them are but the deepened channels of ice-born rivers, and not true valleys. Like the scablands of the Palouse region, invading, but short-lived, floods traversed the area; but they failed in the main to produce broad, stream-scoured surfaces of bare rock. Where they entered preglacial valleys in basalt they were not able to broaden them much. Extensive scablands have been formed only where the preglacial drainage pattern was eroded in a weak, super-basalt sedimentary deposit.

The limits reached by the Spokane ice-sheet west of Cheney and Medical Lake are not well known, since there is no morainal ridging along the margin. The approximate boundary, as shown on the accompanying map, has been located along the southern limits of a basalt plain with much bare rock and a scattering of glacial debris. South of this margin are unglaciated loess-covered hills of mature aspect and the scoured, and in many places canyon-like, glacial drainage channels. The limits as drawn are, perhaps, too far south in places. The ice is not known to have crossed the Columbia between Hellgate and the head of Grand Coulee. It did cross, however, in Douglas County, farther west, and advanced far enough to discharge its waters into Moses Coulee. The Wis-

hills. The till is covered with several feet of loess at Cheney. The loess is deep on all Palouse Hills of eastern Washington, but does not occur on the scablands or on the glaciated plain to the north. It therefore is older than the Spokane glaciation. Since this Cheney till is beneath the loess and probably underlies the Palouse Hills, it is much older than the mature topography. There is no more suggestion of glacial overriding in the shapes of these hills north of Cheney than there is in the typical Palouse region of Whitman County.

On the other hand, certain large pre-basalt hills west of Medical Lake, rising high above the Palouse Hills of the region, do show a prevailing steep northern slope and gentle southern slope, as though they had been overridden by glacial ice. If this profile has had such an origin, it must be ascribed to the pre-Spokane, pre-loess glaciation.

The glacial till reported by Pardee (op. cit.) at "scores" of places over large parts of Lincoln, Spokane, and Adams counties, and as far south as Kahlotus, probably is similarly related to the loess which deeply mantles the Palouse Hills of those counties.

consin glaciation of northern Douglas County was more extensive than the Spokane and obliterated all records left by the Spokane ice.

There are scablands in the northern part of some of these spillways, notably between Davenport and Rocklyn and in the vicinity of Telford. The detailed relations of the largest, at and southwest of Telford, are not yet well known: but concentration in preexisting valleys in basalt was completed in most cases within 10 miles or so of the edge of the ice, and rock-walled canyons with elongated lakes in the bottoms are the rule. The altitudes of the heads of these spillways are not the same, and had not the ice been hard against the unglaciated hills south of the basalt plain, marginal drainage would have carried all waters to the lowest of the group.

Gravel deposits and scattered granite boulders and cobbles are well distributed in these coulees. Gravels are chiefly of basalt and appear as fresh as in the scablands of the Palouse drainage. The terrace forms are indefinite, wide-open gullies have dissected them, and they are but remnants, perhaps miles apart, of former probably continuous fillings. This also is comparable to the gravels of the main Palouse channels.

Because of the prominence of cliffs in these canyons of Crab Creek drainage, another feature is well presented—the talus piles which have formed since the glacial streams abandoned their channels. The cliffs are, without exception, composed of the Columbia lava, and, with very few exceptions, the flows are horizontal or but gently inclined and possess columnar jointing. The conditions of origin produced essentially vertical cliffs, and the rock structures and arid climate have maintained vertical faces during all subsequent wasting of the cliff and growth of the talus.

Except in Grand Coulee and Moses Coulee, which carried Wisconsin glacial waters also, these canyons have been occupied by inconsequential streams since the Spokane glacial floods subsided. The present talus, therefore, is a measure of all post-Spokane disintegration in the vertical walls of jointed lava. In the great majority of cases the talus extends from the rock-floor of the canyon three-fourths to four-fifths of the way to the top (see figures 4 and 7). In the lower cliffs it has climbed even nearer the summit, and rarely the cliff has become obliterated by the mounting waste. The talus slopes range between 20 degrees and 30 degrees, with the average probably between 25 degrees and 30 degrees.

Since conditions of origin, of rock structure, and of climate are sufficiently alike in the Crab Creek and Palouse drainage areas, it follows that relative proportion of talus on cliffs of comparable height may be a valuable criterion to establish more firmly the contemporaneity of glacial

drainage in the two areas. The cliffs of the Palouse scabland, though less prominent on the whole than those of the Crab Creek canyons, everywhere possess the same average ratios of talus height to depth of channel and the same degree of slope. Further use of this criterion will be made when the Wisconsin glacial drainage channels are examined.

Grand Coulee.—Grand Coulee heads in the south wall of Columbia Valley, about 550 feet above the river. At its head it is 1,000 feet deep and about 3 miles wide. In the middle of this valley, 10 miles from the Columbia, stands Steamboat Rock, a basalt mesa with its square mile of summit area at the general altitude of the plateau on either side of the coulee. There are also numerous pre-basalt hills of granite on the floor between Steamboat Rock and the Columbia, formerly buried in the basalt



FIGURE 7.—*Post-Spokane Talus in "The Potholes" south of Trinidad*

and later exhumed in the erosion of the coulee. About 13 miles from the head the canyon narrows to about 2 miles and maintains this width and a depth of about 800 feet as far south as Coulee City. Here the canyon form is lost for 4 or 5 miles, the eastern wall descending, because of a monoclinical flexure, until it is not more than 200 feet above the floor of the coulee. In this broadened portion is a great abandoned cataract with a fall of 400 feet. The width of the falls is nearly 3 miles, the full width of the bottom of the coulee; but it was broken into two different parts in its later history through erosion of the floor above the falls. A central portion of the earlier floor, which escaped much of this erosion, became an island on the brink. The western half, Dry Falls or Grand Falls, is the more definite and in itself was a double fall at the close of the history of this great cataract, with a "Goat Island" in the middle. No water now flows over these falls except in times of heavy rain.

Below the falls the coulee again becomes a canyon, both because of the gorge left by retreat of the falls and because the basalt surface rises in that direction. For 15 miles or so this lower coulee is a wild, spectacular feature, its western wall fully 1,000 feet high and its bottom less than a mile in width. For most of this distance the ancient river flowed on the strike of a monoclinal fold the dip of which averages 45 degrees and is to the southeast. The falls took origin where the glacial stream passed from horizontal flows to the tilted structure, about 3 miles below their present location. Grand Coulee debouches in a broad, shallow structural depression, the Quincy basin. Into this same basin discharges Crab Creek, which carried the combined flow of all of the glacial rivers previously listed.

As above outlined, Grand Coulee is a relatively simple affair, with two canyoned portions separated by a shallower part, due to local structural conditions, with a remarkable waterfall in midlength and with a part of its lower course along tilted flows; but the preglacial conditions and the glacial history are not as simple as in the region farther east.

There is no evidence of a preglacial drainage line along the upper canyon between Coulee City and the Columbia. There are but two tributary gorges in the 30 miles of this canyon and these are short and youthful. A mature topography, untouched by glacial ice or water, lies on the plateau to the east, with no drainage lines leading to the coulee. To the west the plateau was glaciated to the edge of the coulee during the Wisconsin epoch, but preglacial topographic features still control and give no suggestion of drainage toward the coulee. Moreover, the altitude of the basalt on the precipitous edge of the canyon is about that of the Columbia River-Crab Creek divide; and on both sides of the coulee, near the head, especially well shown on the unglaciated east side, is a scabland tract (see figure 3), with the mature hills gone and the basalt etched and roughened by a maze of anastomosing minor channels and rock-basins, separated by low buttes and knobs. Elongated meadows, and even lakes, mark some channel courses. No channels are more than 75 feet deep. Glacial erratics of diorite, argillite, slate, schist, and quartzite occur here and there. Especially significant is the talus, which has climbed three-fourths to four-fifths of the total original heights of the channel walls and nowhere is steeper than 20 degrees. On the east side this summit scabland is 3 miles wide, as wide as the floor of the coulee itself, but 1,000 feet higher. The altitude here is about 2,500 feet above tide.

In order that glacial waters should have spilled across this place, the ice-sheet must have blocked the Columbia, both to the west and the east,

else lower routes in either direction would have taken the discharge. That it was the Spokane ice-sheet is evident from the amount of breaking down of cliffs since the waters ceased to flow. Searching over the basalt, the wide glacial stream finally selected its central portion, now Grand Coulee, for deeper trenching and withdraw from the margins. Only Steamboat Rock records any of the original anastomosis. To what depth the Spokane waters cut in upper Grand Coulee will be discussed under the subject of Wisconsin glaciation.

Hartline structural valley.—The monoclinal flexure along which much of lower Grand Coulee is eroded swings toward the east about 2 miles north of Coulee City and extends beyond Almira toward Hellgate. Another fold, anticlinal in character, lies nearly parallel with it, about 5 miles to the south. The tract between is structurally and topographically a valley and contains a gravelly plain approximately 40 square miles in area. The floor of the coulee at Coulee City is only 200 feet below this flat, and the entire descent to the town from the flat is across gravel. Wells on the flat penetrate sand and gravel to comparable depths.

The drainage of the Hartline gravel plain is largely southward through Deadmans Draw, a tributary of Spring Coulee, 10 miles east of Grand Coulee. Deadmans Draw is but the deepest and most pronounced of a scabland complex of abandoned channels, basins, cascades, and falls, identical in character with and very similar in proportions to those on the plateau along the east side of the head of Grand Coulee. Talus development is the same. Furthermore, the patchy gravel deposits and stranded erratic boulders tell unequivocally of glacial waters escaping southward across the rim of the structural basin.

East of Deadmans Draw, as far as Wilson Creek, are gently rolling hills with concave lower slopes and deep loessial soils, which have never been touched by invading glacial waters; but between the draw and Grand Coulee to the west, and from Coulee City south to Bacon Station, a distance of 8 miles, is a tract which for wild ruggedness is unsurpassed anywhere among the glacial spillways thus far described. The channels are canyons and the knobs are hills 100 to 300 feet high. Stream gravel covers the interchannel hills. The whole area was overrun by the glacial flood out of the Hartline structural valley. Besides this, at least three of the channel canyons lead *out of* Grand Coulee below the falls, but at about the level of the floor above the falls. It is magnified scabland of the Palouse type. One of these channels leads to Spring Coulee, the others converge to Dry Coulee, a small feature debouching into the Quincy structural basin 5 miles east of the mouth of Grand Coulee.

Some of these are truly distributary canyons. They mark a distrib-

utive or braided course of the Spokane glacial flood over a basalt surface which possessed no adequate pre-Spokane valleys. Greater erosion in the tilted basalt on the western margin of this tract finally drew these waters off and down into what has become the lower canyon of Grand Coulee.

There is evidence at the lower end of Grand Coulee that a short pre-Spokane valley was entered a little north of Soap Lake. This lake lies at the mouth of the coulee, where the canyon crosses a low anticline. The syncline between it and the main monocline to the north is low and wide open as a structural valley at the east to the Quincy basin. Some drainage did go through here, but most of it crossed the anticline—a thing which would not have been possible if an antecedent drainage line had not existed at this place.

The original slope on which the glacial waters flowed from the Columbia Valley to the Quincy structural basin was steplike in a general way, a steeper descent existing between the plateau summit to the north and the Hartline basin, and another such on the northern margin of the Quincy basin. These steeper slopes were determined by structure, though they did not conform exactly to it. The monoclinal fold north of the Hartline basin has a maximum dip of 30 degrees. If the slope which the Spokane waters found was only one-third of this, that glacial river, in effectiveness over this stretch, must have been an enormous mountain torrent. The vertically and closely jointed basalt must have been eroded with great rapidity, and, where favorable conditions for sapping were discovered in the channels, falls developed and retreated much more rapidly even than Niagara.

While the talus in the higher abandoned channels reaches up three-fourths to four-fifths of the total original height of the cliffs, that in Grand Coulee itself is only halfway up the cliffs (where the flows are horizontal) and has an almost invariable slope of 35 degrees. It clearly dates from the Wisconsin glaciation, not the Spokane.

Quincy Valley or Basin.—The Quincy structural basin is bounded on the south by the Frenchman Hills anticline, but its drainage escapes southward around the east end of this fold. All glacial drainage routes of the plateau west of Medical Lake, except Moses Coulee, have been traced to it. Enormous quantities of basaltic debris have been swept out of the hundreds of miles of such channels and into this catch-basin. The fill covers 600 square miles and the maximum known thickness is about 400 feet. The lower three-fourths of this fill is clay, silt, and sand, doubtless lacustrine in origin. In this have been found shells of fresh-water boreal mollusks.¹¹ Only the upper 100 feet, approximately, are

¹¹ Schwenneson and Meinzer: Ground water in Quincy Valley, Washington. U. S. Geol. Survey, Water Supply Paper 425 E, 1918, p. 143.

river gravels. About the margin of the basin the gravel is thinner and rests directly on the basalt. The aggradational plain now is dissected by stream-cut valleys which lead southward to a group of very irregular channels eroded in basalt around the eastern nose of the Frenchman Hills anticline and thence west to the Columbia between this fold and the parallel Saddle Mountains anticline. Though this drainage line is named Crab Creek, no surface waters from Crab Creek above the Quincy basin now reach it. Dunes of basaltic sand have closed the lower part of these converging valleys and thus formed Moses Lake.

The group of channels around the end of Frenchman Hills anticline will here be termed the Drumheller channels (see figure 8). The altitude of the basalt floor at the head of these channels is 950 feet and the highest altitude over which the water clearly flowed is about 1,200 feet. The group begins as three canyons of nearly equal dimensions, but for most of its length only two dominant canyoned channels exist, one containing a narrow elongated lake, the other containing Crab Creek. The depth of these canyons averages 200 feet. The whole area, however, is scored and gashed by hundreds of similar smaller channels. The two main gorges separate on an accordant level and unite 4 miles downstream, again accordantly, but 100 feet lower than their point of separation.

South of the Frenchman Hills anticline, Crab Creek Valley turns abruptly west and follows the syncline between this fold and Saddle Mountains anticline to Columbia River at Beverly. A capacious, uninterrupted old river course of low gradient exists along this syncline. It is repeatedly referred to in the literature as the lower part of the Grand Coulee route of the diverted Columbia; and certainly the stream which eroded the two dominant channels of the Drumheller plexus took this course; but at an earlier date, before the present Drumheller channels had been eroded, glacial waters also continued directly southward to pass the east end of Saddle Mountain anticline as well. Channeled scabland and stream gravel with granitic material cover 150 square miles of the region south of the end of this fold. As in the Palouse scabland, hills of mature topography and deep soils, developed in a weak sedimentary (presumably the Ellensburg formation) above the basalt, flank the scabland and are isolated in it. Some of the glacial waters entered Esquatzel Coulee and some went by way of Koontz Coulee to the Columbia near Ringgold. Indeed, Esquatzel Coulee below Connell has been eroded in the scabland subsequent to the maximum flooding.

The waters around the tip of the Saddle Mountain anticlinal nose never cut deeper than 900 feet above tide, while the head of the synclinal course just below the Drumheller plexus is eroded in basalt to 700

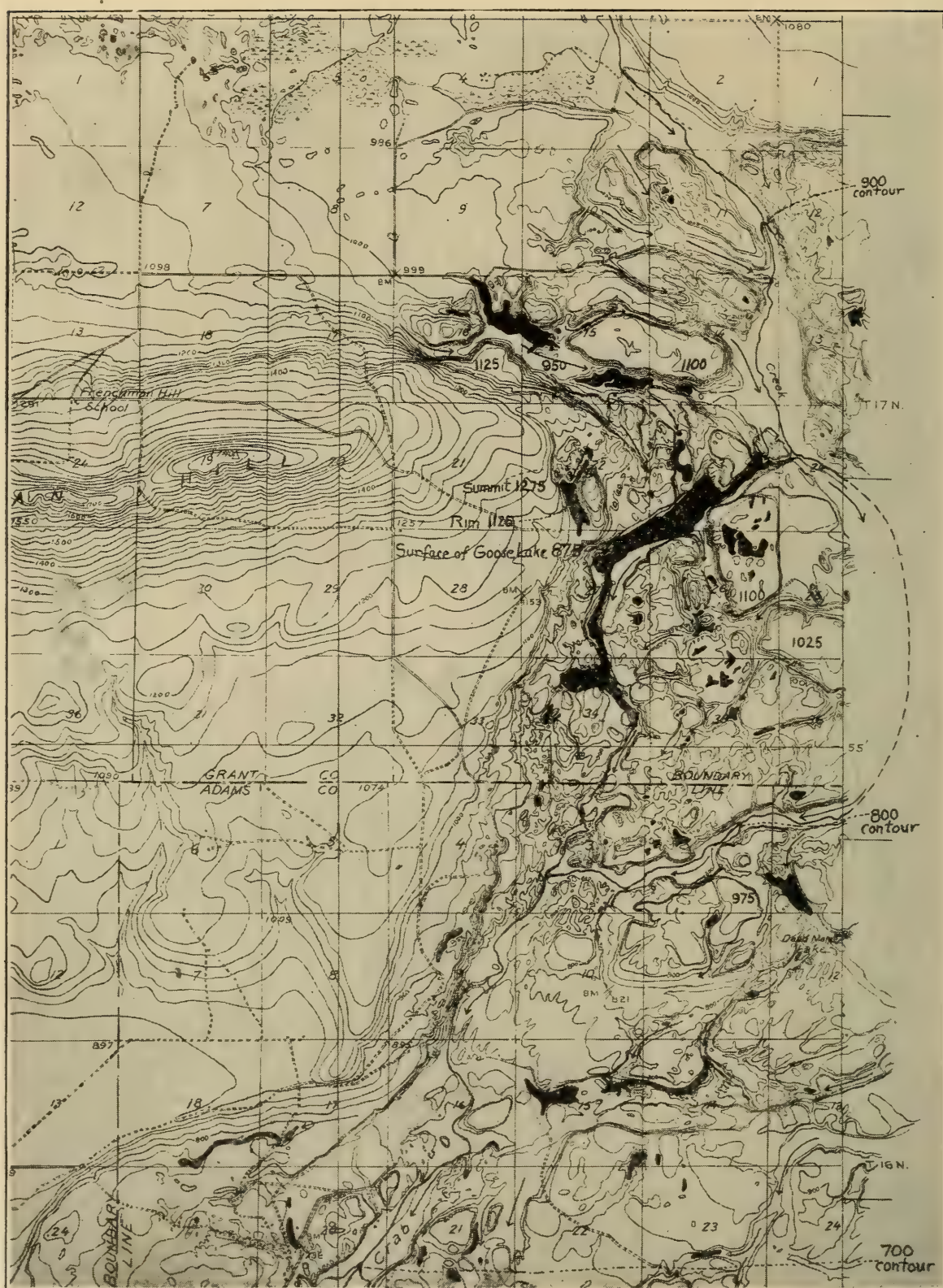


FIGURE 8.—Part of Drumheller Channels Plexus
Channels indicated by arrows; rock-basins in black.

feet above tide. Using the criterion of talus accumulation, most of the Drumheller channels and the existing synclinal river valley date from the Wisconsin glaciation, while the spillway around the east end of Saddle Mountain was formed during the Spokane glaciation. Channeled scabland also lies east of the youthful Drumheller channels and at a higher altitude. It apparently belongs to the Spokane spillways.

It appears, therefore, that when Spokane waters escaped southward from the Quincy basin there was no noteworthy valley for lower Crab Creek and, as in the Palouse country, the flood spread out and found its way among the hills of weaker rock. These hills were removed in the Drumheller tract for a width of more than 10 miles. South of Saddle Mountain the width of the scoured tract is equally great. The flood separated into two parts after passing Frenchman Hills anticline, part continuing south to Esquatzel and Koontz coulees and part turning west in the Beverly syncline. The westward course was eroded more deeply than the southward, so that when, in the succeeding Wisconsin diversion, another flood swept through the Drumheller plexus all of it went westward. The striking features of the present plexus, adjusted to the floor of the synclinal route, were then produced.

Two other outlets for the Quincy basin existed during the Spokane epoch. They are at Frenchman Springs and "The Potholes," two great notches in the wall of Columbia Valley on the western margin of the plateau. Each is an abandoned cataract, to which short channels lead across the western rim of the Quincy basin. "The Potholes" is the best example mapped of a receding waterfall over lava flows which is known to the writer (figure 9). The ancient stream spilled over the Columbia cliffs at an altitude of about 1,200 feet above tide and descended at least 400 feet over two great rock terraces, each with a scarp of about 200 feet. In the upper cliff is exposed a very conspicuous flow with exceptionally large, well developed, and uniform columns approaching 75 feet in length. The flow which holds up the edge of the lower rock terrace is more than 100 feet thick and is composed of uniformly small columns from bottom to top.

The amount of recession in the waterfall is quite unequal in the two rock terraces. In the upper the cataract was double from its beginning, the two parts being nearly equal and receding side by side for nearly two miles. This parallel recession left a great blade of rock a mile and a half long, 1,000 feet wide, and 375 feet in maximum height between them. A huge elongated pothole was left by the recession of each member of the twin upper falls, deepest and widest below the falls. There are great gravel bars in these potholes, especially in the downstream portions. The one below the southern fall is 200 feet thick (figure 10).

The lava flow which causes the lower rock terrace is much more resistant to plucking and sapping than is the upper terrace. This is shown both in the Columbia Valley and in "The Potholes." The current which emerged from the Potholes themselves spread considerably over this terrace and spilled over its edge in a broad sheet which later became somewhat concentrated in four or five different places, so that minor notching of the edge of the terrace resulted; but none of these notches was cut back more than a quarter of a mile.

Above and east of the upper falls is a scabland tract extending two miles farther east across the low rim of the structural basin and very much diversified by ramifying channels and their separating hills. Rock-basins are common, some of them being 40 feet deep. This chan-



FIGURE 10.—One of "The Potholes"

The gravel bar (terrace on left) is 200 feet thick and the cliff back of it is 200 feet high. View is taken looking toward the ancient cataract.

neled tract was an island-studded rapids descending to the brink of "The Potholes" cataract. At the beginning of the cataract this channeled area extended to the original edge of the upper terrace. As the twin falls, narrower than the channel group, receded eastward, some of these channels were left along the edge of the gorge.

The talus accumulations of "The Potholes" are somewhat irregular in height, because of unusually marked differences among the flows in the cliffs, but the large majority constitute three-fourths or more of the total height of the cliffs (see figure 7). "The Potholes" cataract was formed at the time of the Spokane glaciation by discharge from the Quincy basin. The Columbia Valley here was nearly or quite as deep at that time as it is today. The structural basin was aggraded to the level of this western rim and gravel was carried completely across from

Crab Creek and Grand Coulee. As in the Hartline structural basin, the Spokane floods found the depression only partially filled, but left it brimming over with waste.

The Frenchman Springs cataract, 8 miles south of "The Potholes," functioned at the same time and developed a double fall also, but carried a smaller quantity of water. The northern of the two falls here outran the southern in its recession and at the close of the history of the cataract was carrying all of the discharge.

Why did not Wisconsin waters use the Frenchman Springs and Potholes cataracts? There are two possible answers: (1) Spokane discharge through Drumheller Channels eroded this spillway more than it did the rapids above either of the two cataracts, and (2) post-Spokane but pre-Wisconsin warping depressed the Drumheller tract relative to the channels above the two cataracts enough to cause complete Wisconsin diversion to the southern route; and, of course, it is possible that some combination of both occurred.

MOSES COULEE

This coulee (not to be confused with the valley which contains Moses Lake) ranks second in spectacular proportions only to Grand Coulee. It lies a few miles west of Grand Coulee and leads southwestward directly to the Columbia, 10 miles above "The Potholes." Its length of 40 miles is divisible into three portions, an upper and a lower canyon separated by a broad, shallow tract in a synclinal valley. The upper canyon is eroded in the gentle southward dip slope of this part of the plateau. Its depth averages about 200 feet. Dip of the basalt is greater than descent of coulee floor. The inclosing walls thus become lower until they virtually disappear and the floor of the canyon becomes the floor of the synclinal valley. Here the coulee turns abruptly to the west and follows the axis of the syncline for 6 miles. At Palisades it turns southward again and leaves the syncline to cross a broad uplifted area, or flat-topped anticline, the Badger Mountain fold. The lower canyon across this fold is 900 feet deep.

The lower canyon has been extended upstream by headward erosion about half the length of the synclinal portion. Here it abruptly ends at the foot of a cliff across the coulee. Two great castellated buttresses face down the coulee, with lesser walls connecting them. This notched cliff clearly was a waterfall, and before the deep notching it was comparable in height to Grand Falls at Coulee City.

From this transcoulee cliff to the lower end of the upper canyon is a tract, 5 or 6 miles long and nearly as wide, where the basalt floor of the syncline was widely overrun by a great stream which formed a complex

of anastomosing channels with rock-basins and cataracts, leaving isolated knobs and buttes irregularly disposed in a perfect maze (see figure 4). Bare rock or rocky talus covers the area, whereas both canyoned portions have no rock-floor exposed. There is a total descent of 600 feet along this tract. Most of the channels have noteworthy talus accumulations, amounting to three-fourths or four-fifths of the total depths. Only the lower and central channels bear talus comparable to that in Grand Coulee and Drumheller channels. Erratics of granite, quartzites, etcetera, lie here and there, even on the highest of these eroded surfaces.

In the upper canyon, north of the moraine built by the Okanogan lobe during the Wisconsin glaciation, talus is but halfway up the cliffs. Below the moraine some talus piles seem to be of Spokane age, some of Wisconsin, and there is other evidence that Wisconsin waters only partially cleaned away the preexisting cliff waste. In the lower canyon the talus dates back to the Spokane epoch. If there is any record of Wisconsin waters, it is in the gravel fill, more than 200 feet deep, 3 miles from the head of this canyon, and possibly in the existence of a prominent rock terrace, not more than 100 feet above the aggraded floor of the canyon, a few miles south of Palisades. If trenching by Wisconsin waters was performed anywhere in the lower canyon, it was in the production of this terrace.

Moses Coulee, as a drainage line, antedates the Spokane glaciation. Tributary valleys, well developed in the basalt, are recognizable as far north as Mansfield, and the upper canyon itself extends 6 or 8 miles north of the Wisconsin terminal moraine; but the best evidence is in the lower coulee. The cliffs here are deeply notched by wide-open V-shaped tributary valleys. Many notches are two-thirds or more as deep as the main canyon. These notches give the cliffs a striking resemblance to a series of great rounded gables in alignment (figure 11). The slopes of these tributary gorges are graded and covered with sage and grass. Rock ledges in them are rare. They clearly are the relics of a pre-Spokane drainage line, the trunk valley of which was entered and greatly enlarged by the Spokane waters. Both widening and deepening in the basalt occurred and the tributaries were left hanging. They have since attained topographic adjustment by building large alluvial fans out on the canyon floor. Furthermore, Moses Coulee crosses the Badger Mountain fold, as already noted. Like the crossing of the Soap Lake anticline by Grand Coulee, this records an antecedent course determined long before the Spokane glaciation.

Spokane waters could not have entered Moses Coulee if the parent ice-sheet had not pushed across or at least well up on the divide south of the

Columbia. Therefore, though no till or striæ left by the Spokane ice are known on the south side of the Columbia west of Grand Coulee, the operation of both Moses and Grand coulees proves that Cordilleran ice did cross the Columbia, and the Spokane features of Moses Coulee prove that it reached nearly as far south as it did in the later Wisconsin epoch.



FIGURE 11.—*Cliffs of lower Moses Coulee*

The cliffs are 900 feet high. There are shown the pre-Spokane tributary valleys, the main canyon of Spokane age, and the post-Spokane talus.

THE WISCONSIN GLACIATION

The terminal moraine deposited by the Cordilleran ice-sheet in north-eastern Washington during the Wisconsin glaciation has been traced in part by Salisbury and student assistants.¹² The ice reached the Columbia Plateau in two places. One of these was south of the capacious Okanogan River Valley, and the lobe which spread out on the plateau here reached 35 miles beyond the river and was nearly 50 miles wide. The other place was on the lower Spokane River and was of little consequence. The only noteworthy Wisconsin drainage derangement of the entire plateau was the reoccupation of Grand Coulee and lower Crab Creek. Through this route was poured the water from the Cordilleran ice-sheet along the entire front from the Rocky Mountains to the Okanogan lobe. Though the Spokane ice yielded much greater volumes of water, all told, than did the Wisconsin, it was carried by many valleys, no one of which ever contained the quantity which went through Grand Coulee during the later diversion. That flood was greater than the deep-

¹² R. D. Salisbury: Glacial work in the western mountains in 1901. Jour. Geol., vol. 9, 1901, pp. 721-723.

George Garrey: Glaciation between the Rockies and the Cascades. Master's thesis, in library of Department of Geology, University of Chicago.

ened main channel of the Grand Coulee system could contain and all but one of the tributary canyons again were in operation. The level of the Hartline gravel plain was not reached, however, and Deadmans Draw remained untouched. The evidences for this conclusion are the character of the talus in Deadmans Draw, already outlined, and the gravel deposits in and at the mouth of Dry Coulee. These latter deserve a brief description.

The gravel terraces of Crab Creek Valley above the junction of Dry Coulee, at Adrian, are fragmentary remnants in protected places and in general do not have sharp terrace forms. Most of the valley floor is at the floodplain level; but 3 or 4 miles east of Adrian the floodplain is narrowed almost to obliteration by a great gravel fill whose surface is about 100 feet above the valley bottom. The creek here flows in a narrow inner valley, close to the southern wall of the rock-cut main valley. The surface of the gravel fill rises northward across the width of the main valley and continues up Dry Coulee, which in its lower part is likewise nearly filled. Though there is little difference in amount of weathering between this gravel deposit and the Spokane gravel in Crab Creek Valley east of Dry Coulee, it clearly is much younger in terms of erosion. Its dissection has just begun. It is traceable back up Dry Coulee to the three tributary canyons which lead southward out of the upper walls of Grand Coulee. In all probability it is a deposit made by the Wisconsin floods before the lower canyon of Grand Coulee was deepened sufficiently to take care of the entire discharge.

Lower Grand Coulee therefore appears not to have been much deeper at the beginning of the Wisconsin discharge than the floor of these tributary canyons. Grand Falls probably was formed during this epoch, taking origin at the head of Blue Lake, where the coulee begins its course in the tilted flows of the monoclinial flexure. This cataract has receded about 3 miles to that portion known as Dry Falls, west of Coulee City, and about 5 miles to the less pronounced falls at the head of Deep Lake, about a mile south of Coulee City. They could not have existed farther down the coulee, for there it is eroded on the strike of flows whose dip, on the average, is 45 degrees.¹³

Previous descriptions of the relation of the Okanogan lobe to Grand Coulee state that the ice-sheet deployed eastward only to the edge of the upper canyon; but the granite knobs in Grand Coulee above Steamboat Rock are strongly glaciated down at least to the level of the present

¹³ O. E. Meinzer, in "The glacial history of Columbia River in the Big Bend region" (*Jour. Wash. Acad. Sciences*, vol. 8, 1918, pp. 411-412), argues that the falls have receded for 17 miles, virtually the full length of the lower coulee.

aggraded floor. The northwest sides of these hills are notably smoothed and rounded and some bear striae. The orientation varies, as would be expected on rugged rock hills overridden by ice, but is not far from northwest-southeast. The southeast sides are steep and jagged. The sheeted structure of the granite apparently has lent itself to plucking by the ice. Furthermore, the summits of the basalt bluffs on the western side of the coulee also are striated in approximately the same directions, and striae and abundant large granite erratics are reported on the top of Steamboat Rock (figure 12).

The glaciation of these granite hills and the basalt hill south of them occurred at the maximum deployment of the Wisconsin ice on the plateau. It can not be a record of the Spokane glaciation, for these granite



FIGURE 12.—*Steamboat Rock*

Steamboat Rock is in the middle of the Grand Coulee and near the head. The talus is of post-Wisconsin age.

hills then were buried hundreds of feet beneath basalt and have been exhumed by the erosion of both Spokane and Wisconsin glacial drainage. If it be argued that this exhumation occurred during the early stages of the Spokane glaciation, the ice later advancing into the head of Grand Coulee, the answer is that these exposed glaciated surfaces would have been obliterated during the interglacial interval.

What became of the Wisconsin drainage when the Okanogan lobe crowded down into the head of Grand Coulee? Since the Spokane spillways to Palouse River are lower than all others on the plateau except Grand Coulee, and since there was an eastward route open to them in front of the Wisconsin ice, it might be expected that for a short time glacial drainage would be diverted to the Palouse. But reexamination of these spillways has found no signs of such occupation. Furthermore,

the granite hills in the coulee close to the eastern wall do not show glacial smoothing, though all others do. This is interpreted to mean that the escaping waters kept a passage open along the eastern edge of the ice, which thus failed to close the coulee completely. All the water at this time flowed on the east side of Steamboat Rock, and perhaps the eastern wall of the canyon here was eroded back to expose the unglaciated granite hills and to make the greater width which the canyon possesses between Steamboat Rock and the Columbia.¹⁴

A widespread submergence of the lower Columbia Valley is known to have occurred during the Wisconsin glaciation.¹⁵ It is recorded by berg-floated erratic boulders, some of great size, scattered widely in the Columbia Valley below the present altitude of about 1,250 feet above tide. The submergence was due to a lowering of the entire region relative to sealevel. The ponded waters rose sufficiently high to spread over considerable areas of the plateau, and glaciated boulders now are found where glacial ice or glacial streams could not possibly have transported them. Most of these boulders, and all of the large ones, are of granite. They are strikingly abundant in some parts of the Quincy basin, a distribution which points to Grand Coulee as the route by which they reached the basin. After one has seen the dozens of granite knobs in upper Grand Coulee, heavily glaciated on the northwest and apparently much plucked on the southeast, the conviction grows that most of these large granite fragments were quarried in the head of the coulee when the Okanogan lobe was at its maximum deployment. The ground moraine of the Okanogan lobe has but a small percentage of granite boulders compared with basalt boulders, and a still smaller percentage of large granites compared with large basalts. It appears, therefore, that some special condition, such as that outlined above, must have existed to reverse the ratio among the berg-floated boulders.

The upper limit of these erratics earlier reported was 1,283 feet above tide, and in the eastern part of the Quincy basin none have since been found above that altitude; but on Babcock Ridge, near Trinidad, boulders of gneiss, granite, quartzite, schist, slate, and argillite have recently been found as high as 1,350 feet above tide. On the hills northeast of Trinidad a "nest" of twelve granite fragments from an inch to 16 inches in diameter and one quartzite pebble have been found—all within a radius of 15 feet and at an altitude of 1,400 feet above tide. These seem clearly

¹⁴ K. Oestreich ("Die Grande Coulée," Transcontinental Excursion of 1912, American Geographic Society, 1915, pp. 259-274) has suggested, and J. T. Pardee ("Glaciation in the Cordilleran region," *Science*, vol. 56, December 15, 1922, pp. 686-687) has asserted, that an ice-stream traversed Grand Coulee.

¹⁵ J. H. Bretz: The late Pleistocene submergence in the Columbia Valley of Oregon and Washington. *Jour. Geol.*, vol. 27, 1919, pp. 489-506.

to have been carried here in floating ice. Either the upper limit of the submergence was greater over the plateau than has been thought or there has been post-Wisconsin upwarping in the vicinity of Trinidad. The latter seems the more probable.

Pardee has described a deposit of silt with sand and gravel, the Nespelem formation,¹⁶ in the Columbia Valley above Grand Coulee. This he believes to be of Wisconsin age and to have been caused by a lowering of the region such that the upper surface of the deposit (1,700 feet above tide) records the sealevel of that time. What is taken to be a part of this formation lies on the floor of Grand Coulee about Steamboat Rock and the granite hills. Its upper surface here is about 1,650 feet above tide and *it is seasonally banded*. From its position, it obviously was deposited after the margin of the Okanogan lobe and the diverted glacial Columbia had abandoned Grand Coulee. It therefore was deposited after the berg-borne debris had been carried through the coulee. None of this silt has been recognized in the Quincy Valley or in the Columbia Valley below the Okanogan lobe. It may be a record of the submergence, as are the berg-carried erratics. It also may be related to the ponding of the Columbia by the Okanogan lobe, or by the large Wisconsin Valley train from the Okanogan Valley, which Pardee describes and which was formed during the retreat of the Cordilleran ice-sheet.

Most of the fill of the Quincy structural basin, as shown by well records, is clay and silt. The Pleistocene boreal mollusks reported from the upper part of the clay¹⁷ suggest that it was deposited while a glacial climate prevailed, but probably not when the glacial waters were being discharged across the northern rim of the plateau, for the gravels overlying the clays were then carried into the basin.

There appears to be one great summit plane of the gravels, now dissected into four parts. The altitude of the northern part of each terrace is about 1,250 feet above tide. The surface (restored) slopes toward the Frenchman Springs and Potholes cataracts on the western margin of the basin and toward the Drumheller plexus on the southern margin. A continuous grade exists westward into the bottoms of the eroded channels at the head of the cataracts, but to the south the gravel terrace is 150 feet above the floor of Crab Creek Valley immediately adjacent and as high as the basalt buttes among the channel heads.

This gravel fill probably dates back to the Spokane epoch, though some of it may have been aggraded during the early part of the Wisconsin

¹⁶ J. T. Pardee: Geology and mineral deposits of the Colville Indian reservation, Washington. U. S. Geol. Survey, Bull. 677, 1918, pp. 28-29 and 47-50.

¹⁷ Schwenneson and Meinzer: Ground water in Quincy Valley, Washington. U. S. Geol. Survey, Water Supply Paper 425 E, 1918, pp. 143-144.

diversion, as that at Adrian, where Crab Creek was completely blocked by Wisconsin gravel. The basin fill is not dissected, however, as are Spokane gravel terraces in the upper Crab Creek drainage. This may be because it does not lie in a narrow valley and because it is very porous, absorbing all rainfall and allowing no surface streams to form. The dissection takes the form of three large meridional channels converging to the Drumheller plexus. Two of these lead from the mouth of Grand Coulee; the third and easternmost leads from upper Crab Creek near the mouth of Dry Coulee. It seems probable that, though some interglacial trenching by Crab Creek occurred, these channels were eroded largely by the diverted Columbia during the Wisconsin epoch, the erosion being rendered possible because of the contemporaneous deepening of the two main Drumheller channels. The western channel is broad but much shallower than the other two. Its proportions indicate that it is the channel of a large stream, not the valley of a small one, and its shallowness indicates that it was abandoned early in the Wisconsin dissection of the fill.

The mouth of Grand Coulee is an undrained depression containing Soap Lake. It is dammed by the gravel deposits in Quincy Valley. All drainage of the lower canyon of Grand Coulee comes to it, upper Crab Creek flows to it (when it flows at all), and the neighboring gravel plain, through an arc of 180 degrees, from east through south to west, slopes back toward it. The slope in this arc is gentle and clearly constructional. Whether this back slope is wholly of Wisconsin age or dates in part from the Spokane epoch, it seems clear that it is a graded subfluvial slope, adjusted to the traction load and the velocity of a current emerging from Grand Coulee. The velocity here was greatest within the rock walls of Soap Lake and decreased rapidly as the waters spread out in the Quincy basin. The depth of that glacial stream can not be measured, however, by the difference in altitude of lake floor and gravel rim. During the later stages of Wisconsin discharge, as the Drumheller channels were gashed more deeply and the three channels eroded across Quincy basin fill, notches appeared in the rim of the gravel barrier and the constricted portion containing Soap Lake probably was then deepened.

In all gravels in glacial spillways across the Columbia plateau, basalt is by far the most important constituent. Only a small fraction of 1 per cent is of other material. It therefore is not to be considered as glacial outwash in the ordinary sense, for it has not come from the Cordilleran glacial drift. It represents basalt eroded by the high-gradient glacial streams in producing scablands and canyoned coulees.

Thus a brief episode in the latter half of the Pleistocene (the maximum of the Spokane glaciation) introduced conditions under which the

scablands, much more than a thousand square miles of the plateau, and more than a tenth of the total area of the plateau (as the term is used in this paper) have been denuded of overlying sedimentary deposits by running water. But, despite the enormous amount of erosion by escaping glacial waters in both Spokane and Wisconsin epochs, no permanent derangement of drainage lines, save that of the Palouse from Hooper to Snake River, resulted. The Palouse formerly flowed to Esquatzel Coulee by way of Washtucna Coulee. Its course to Snake River was shortened 50 miles by this diversion, probably during the Spokane epoch.

The Wisconsin history of Drumheller channels and Moses Coulee has been outlined in the description of these features under "Spokane Glaciation." It remains to note that the small amount of erosion in the synclinal plexus of Moses Coulee and the small valley train built by drainage from the tip of the Okanogan lobe suggest that this lobe may have evaporated in considerable part. This suggestion of large evaporation may also explain the relatively small amount of Wisconsin water which came from the Cordilleran ice east of the Okanogan lobe.

DISCUSSION

DR. M. M. LEIGHTON: The speaker is to be congratulated on the character of the work he has done in eastern Washington. A few years ago I had the opportunity to see some of the features which he describes, and the case for at least two glaciations is perfectly clear and, as he suggests, there may have been three. In support of this, I may say that in a gravel pit in the southwestern part of Spokane I found balls of apparently old glacial till in what seemed to be gravel of Spokane age.

MR. OSCAR E. MEINZER: I was especially interested in this excellent paper, because of my own brief field work a few years ago in this region. The glacial features of the region are on a grand scale and very striking. I understand that in the Spokane Stage the lake in Quincy Valley discharged directly into the gorge of the Columbia and also through the outlet east of Frenchman Hills, and that the latter was over lava rock. How is the deep trenching of the plain in Quincy Valley during the Wisconsin Stage accounted for?

Author's reply to Mr. Meinzer: Only the upper or gravelly part of the Quincy Valley fill is surely of Spokane age. Wisconsin waters added but little to this deposit. They eroded it instead, because of downcutting in the basalt at the Drumheller Channels at this time. All the remarkable features of that tract are in basalt and were produced largely by Wisconsin waters.

Brief remarks were also made by Mr. Leverett, with reply by the author.

RANGE AND DISTRIBUTION OF CERTAIN TYPES OF CANADIAN PLEISTOCENE CONCRETIONS¹

BY E. M. KINDLE

(Presented before the Society December 29, 1922)

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INTRODUCTION

Concretions do not lend themselves to the exact methods of description used by the mineralogist. Paleontologists are likely to mention them only casually in connection with the fossils which they often inclose. Other geologists are apt to let them severely alone save for the briefest possible mention. Concretions may therefore be said to belong to a sort of "no-man's-land" in geology. Notwithstanding excellent descriptions of particular kinds of concretions which have appeared, we are still without criteria which will enable geologists to agree as to whether certain forms are of organic or inorganic origin. Cases have been recorded

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where structures of undoubted concretionary origin have been considered fossils by some geologists.² A number of forms which have been described as fossils are considered by some competent students of concretions to be partially or entirely due to inorganic agencies. As long as diversity of opinion exists as to whether a large class of structures³ are fossils or concretions, excursions into this imperfectly understood field by paleontologists require no apology.

Certain forms figured in this paper might be considered either concretions or fossils, or neither, according to the predilection of the individual observer. This border land in which nomenclature should be applied in no dogmatic fashion may be studied probably to better advantage in the Pleistocene than in older rocks because of the recent date of development of the structures. Chiefly for this reason the writer has chosen to discuss some of the Pleistocene concretions in his collections instead of those from older rocks.

Some of the curious forms found in the Champlain clays of New England began to arouse curiosity at a very early date. John Winthrop,⁴ the colonial Governor of Connecticut, sent a collection of small spherical concretions exposed by a landslide to the Royal Society in 1620 which he described as "round bullets of clay" from the "inward bowels of ye hill." . . . "but how they should be within ye hill is strange to consider." Since the days of John Winthrop many geologists have given thought to the question which perplexed the old colonial Governor. Various references to the concretions of the Connecticut River Valley appear in the papers of Hitchcock and other New England geologists. They have been more elaborately described than any other American concretions in a beautifully illustrated memoir.⁵

The concretions to be described in the following pages represent collections from the Pleistocene clays of Labrador, where Pleistocene fossil-bearing concretions have not been previously found; from the Slave River, the Ottawa Valley, and Endako, British Columbia. These were collected by the writer with the exception of the specimens from British Columbia, which were obtained by Mr. C. J. Kettle and Dr. George Hanson.

² W. T. Bell: The remarkable concretions of Ottawa County, Kansas. *Am. Jour. Sci.*, vol. xi, 1901, pp. 315-316.

³ a. O. Holtedahl: On the occurrence of structures like Walcott's Algonkian algae in the Permian of England. *Am. Jour. Sci.*, vol. 1, February, 1921, p. 196.

b. G. Abbott: Notes on concretions. *Proc. Geol. Assoc.*, vol. xxvii, 1916, pp. 192-197.

c. C. D. Walcott: *Smithsonian Misc. Coll.*, 64, no. 2, 1914.

⁴ John Winthrop: *Mass. Hist. Colls.* (5), vol. viii, pt. 4, p. 128. Winthrop Papers.

⁵ Mrs. J. M. Arms Sheldon: *Concretions from the Champlain clays of the Connecticut Valley*. Cambridge, 1900.

Wherever careful attention has been given to concretionary inclusions in sedimentary rocks, the limited stratigraphic range of particular types has been evident. This feature and the relation of form to kind of sediment are the main facts to which attention will be given in the following observations on these specimens. Direct response to the physical features of the beds in which concretions occur is shown in their shape and size. Concretions frequently reflect in their peculiarities certain contrasts in the composition and texture of successive beds of a terrane. They may therefore often serve as an index to differences which on casual observation are not always obvious. This characteristic response of concretions to the character of the matrix appears to be illustrated in the *Dæmonelix* beds which led Barbour, by the increasing diversity of forms between the bottom and top of his section ranging from the *Dæmonelix* cakes to "devil's corkscrews," to suggest that they represented "possible steps in the phylogenetic history of a new fossil." * Illustrations of this response to physical features of the sediments will be pointed out in some of the observations which follow.

NOMENCLATURE OF CONCRETIONS †

No elaborate or exhaustive discussion of the nomenclature of concretions can be attempted here, but some reference to the subject seems essential to a clear understanding of the detailed descriptions which follow.

Concretions consist of aggregates of rock-forming materials differing in structure or composition from the inclosing rock and frequently amorphous or colloidal in character. Organic agencies may or may not play a part in their formation. In place of the ordered arrangement of molecules present in a crystal, each surrounded by others of the same kind, the concretion generally shows amorphous structure frequently associated with varying chemical composition in different parts.

Certain classes of concretions with well defined and uniform types of symmetry, like oolites and cone-in-cone, have received widely accepted distinctive names and are not generally referred to under the name of concretions, although they belong in this general category.

Holtehdahl[‡] has proposed that we use for structures which appear to be

* E. H. Barbour: Nature, structure, and phylogeny of *Dæmonelix*. Bull. Geol. Soc. Am., vol. 8, 1897, p. 306.

† The author is indebted to Dr. George Abbott for the loan of several papers used in the preparation of this section and in the bibliography at the end of the paper.

‡ O. Holtehdahl: Am. Jour. Sci., vol. 47, 1919, p. 95, and vol. 1, February, 1921, p. 195.

genetically related to oolites Kalkowsky's⁹ name *Stromatolites*, "a term that includes those laminated concentrically built structures occurring in limestone and dolomites."

A number of terms have come into local use for structures which are generally recognized as concretions. Among these are the *eyestones* or *morpholites* of Egypt,¹⁰ the *ballstones* of the English Silurian rocks,¹¹ and the *iron pipes* of the Folkestone sands.¹²

The *beekites*¹³ consist generally of "chalcedonic rings circling lime nodules or shells." The Irish term *paramoudra*¹⁴ refers to remarkably large flint cylinders.

Calcareous concretionary structures afford no more remarkable forms than the concentrically zoned concretions of the Fulwell Hill quarries in England, some of which bear a striking resemblance to *Newlandia major* and other Precambrian fossils as Abbott¹⁵ and Hortedahl have pointed out.

The Champlain clay concretions of New England have generally been known to Hitchcock and later geologists as *claystones*.¹⁶

Concretions found in the Norwegian Pleistocene clays are known to Scandinavian geologists as *marlekor*, or fairy stones, and *näkkebröd*. T. Kjerulf¹⁷ has published good figures of these.

Certain of these *marlekor*, or *imatra stones*,¹⁸ as they have also been called, are considered true concretions by some geologists and clay pebbles by others. They have been described by Sars and Erdmann¹⁹ from the glacial clays of Sweden.

Quirke²⁰ has described, under the name *marlekor* or *imatra stones*, clay inclusions from the Pleistocene of Canada which he does not con-

⁹ Kalkowsky: Oolith and Stromatolith in Nordlichen Bundsandstein, Zs. dd. geol. Gesellsch., 1908, p. 60.

¹⁰ Mary S. Johnston: Geology and physiography in Egypt. Geographical Teacher, no. 49, vol. ix, pt. 3, 1917, p. 142.

¹¹ Mary S. Johnston: Proc. Geol. Assoc., vol. xxv, 1914, p. 193.

¹² George Abbott: Tubular structures in rocks which are probably due to osmotic action. Trans. S. E. Union of Sci. Socs. (Eng.), 1916, p. 20.

¹³ T. M. McKenny Hughes: On the manner of occurrence of beekite and its bearing upon siliceous beds of Paleozoic age. Mining Mag., vol. 8, no. 40, 1889, pp. 265-271.

¹⁴ J. W. Judd: Students' Elements of Geology (C. Lyell), illustrations, p. 256, 1896.

George Abbott: Concretions. S. E. Natl. (Eng.) for 1907, p. 71, pl. 12, fig. 11.

¹⁵ George Abbott: Notes on concretions. Proc. Geol. Assoc., vol. 27, 1916, pp. 192-197.

¹⁶ J. M. Arms: Clay concretions of the Connecticut River. Can. Rec. Sci., vol. 4, 1891, p. 238.

¹⁷ T. Kjerulf: Udsigt over det sydlige Norger Geologi, Christiania, 1879, pp. 4-9, pls.

¹⁸ G. F. Parrott: Mem. de l'Acad. Imp. des Sciences de St. Petersburg, 1849, and "Recherches physiques sur les pierres d'Imatra," 1840.

¹⁹ A. Erdmann: Expose des formations quaternaires de la Suede, Stockholm. 1868, pp. 84-87.

²⁰ T. T. Quirke: Can. Geol. Surv., Mem. no. 102, 1917, p. 56, pl. 85.

sider true concretions. Liesegang, Richters, and Wilson regard similar forms as representing true concretions.²¹

Todd²² divided concretions into four classes based on their method of growth. These are *accrétions*, *intercretions*, *excretions*, and *incretions*. The first grow from the center outward in a regular manner. The incretions are the forms commonly known as septaria, which result from irregular and interstitial growth, causing internal fissures. In excretions, according to Todd, growth proceeds from the exterior inward. Incretions are those cylindrical forms with a hollow core.

Dr. George Abbott²³ has published in tabular form a classification of concretions showing the form and composition of the varieties recognized.

J. I. Northrop,²⁴ a zoologist, introduced the term rhizomorphs, which was preoccupied by the botanists for the same class of structures called incretions by Todd. The substitute proposed for these terms by the writer will be indicated elsewhere in this paper.

William Hill²⁵ has, on the basis of structure and texture, recognized seven types of siliceous concretions, which are included under the names flint, chert (four types), opalite, and hornstone.

Professor Grabau has recognized two types of concretions, distinguished from the point of view of origin and relationship to the inclosing beds: "(1) Those forming as contemporaneous accumulations, afterwards buried by clastic or other strata; and (2) those forming within the strata after their deposition." Chemically formed oolites and pisolites Grabau includes under contemporaneous concretions.²⁶

W. A. Tarr²⁷ in a recent paper has classified concretions as to origin in essentially the same way as Grabau, using for the two classes recognized the terms syngenetic and epigenetic. Concretions of the first-named class were formed at the same time as the inclosing beds, while epigenetic concretions were developed subsequent to the adjacent beds.

Richardson,²⁸ considering concretions from the standpoint of the rela-

²¹ a. R. F. Liesegang: *Geologische diffusionen*, Dresden and Leipzig, 1913, p. 159.

b. F. Richters: *Ueber Marlekor*, Prometheus, 23, 1912, p. 697.

c. M. E. Wilson: *Geol. Surv. Can., Mem.* 39, 1913, p. 105, pl. xxvii.

²² J. E. Todd: *Concretions and their geological effects*. *Bull. Geol. Soc. Am.*, vol. 14, pp. 353-360.

²³ George Abbott: *Concretions*. *S. E. Natl. (Eng.)* for 1907, pp. 66-81, pls. 13-18.

²⁴ J. I. Northrop: *A Naturalist in the Bahamas*, 1910, p. 40.

²⁵ William Hill: *Flint and chert*. *Proc. Geol. Assoc.*, vol. 22, 1911, pp. 61-94 (93-94).

²⁶ A. W. Grabau: *Principles of stratigraphy*, 1913, p. 718.

²⁷ W. A. Tarr: *Syngenetic origin of concretions in shale*. *Bull. Geol. Soc. Am.*, vol. 32, 1921, p. 373.

²⁸ W. Alfred Richardson: *The relative age of concretions*. *Geol. Mag.*, vol. lviii, 1921, pp. 114-124.

tive age of the inclosing rock, divides them into three classes—*contemporaneous*, *penecontemporaneous*, and *subsequent*.

The concretions described in this paper all belong to the class called “epigenetic” by Tarr—the “subsequent” concretions of Richardson.

LABRADOR CONCRETIONS

The Labrador Pleistocene beds exposed in the Lake Melville district, in the eastern part of the Labrador peninsula, may be divided into three horizons. The base of the series consists of laminated fine-textured marine clays containing at many points an abundant marine fauna. These are followed by beds of similar appearance, but with more perfect and conspicuous lamination, which are nearly, if not quite, barren of fossils. The uppermost beds of this series are Pleistocene sands.

Small concretions occur sparingly in the beautifully laminated clays which represent the upper portion of the Pleistocene clay beds. These concretions were noted at a single locality only on the Red River about 25 miles northeast of Grand Lake. Here they are of a pale chocolate color and show no considerable variety of form. These concretions are without the organic nuclei so commonly found in the concretions of the lower clays of the Lake Melville basin. Their chocolate-brown color also distinguishes them from the concretions in the older clays.

Concretions were found at a number of localities in the lower clays. Their general appearance is indicated by the illustrations, plates 5 and 6. The principal localities from which concretions were collected in the Lake Melville district are the clays at the lower end of the Muskrat portage, on the Hamilton River; a point on the south bank of the Hamilton about 7 miles below the Muskrat Falls; the banks of the Kenemich River; and the exposure of the clays west of Long Point, on the south shore of Lake Melville. Slightly different horizons are probably represented in these different localities. These localities afford a large variety of forms, some of which are shown in the illustrations on plate 5. The concretions from the Muskrat Rapids locality are mostly of a subspherical symmetrical type (plate 6, figure 3). At another locality 7 miles below Muskrat Rapids the concretions are all of an elongated type, some of them roughly resembling slightly flattened cylinders, others of rib-like shape with rounded ends; these and many other peculiar elongate shapes are found here (plate 5, figures 5-8).

Sharp contrasts between the composition of the outer shell and the interior portion is one of the characteristics worthy of note in the Labrador concretions from certain localities. The elongate forms found on

the south bank of the Hamilton River are composed chiefly of argillaceous calcium carbonate. A thin shell of limonite surrounds this interior portion of the concretion. Many of these concretions consist of hard, well-indurated material encased in a thin shell, sometimes a sixteenth of an inch or more in thickness, consisting of a very soft material easily indented by a knife point or the thumb nail. Some of the Kenemich River localities also furnish types of concretions not seen elsewhere. At one of these all of the concretions consist of sand cemented by iron which has accumulated along the sides of small roots. The roots are sometimes visible in the sections of these pipelike concretions of sand and iron, and when broken into sections the central opening left by the root gives them the appearance of large disk-shaped beads.

The Lake Melville concretions show every possible relationship to the fossil Pleistocene shells from that with the shell occupying the position of a typical centrally placed nucleus, as in figures 1 and 2, plate 6, to examples in which the shell is entirely on the surface of the concretion, as in figure 3, plate 6. Other specimens show opposite ends of shells like *Mytilus* extending out on either side of an irregular-shaped concretion which has completely enveloped the middle portion of the shell (plate 6, figure 4). Many examples occur in which the concretion is attached to a small portion of a granite pebble (plate 5, figures 2 and 3), while others have numerous pieces of fine gravel projecting from their sides. The numerous rings which mark the surface of many of the subspherical concretions at right angles to the shorter axis represent the lamination of the beds in which they occur. Such concretions when ground show the lamination planes continuing through the concretion in line with the encircling rings on the surface (plate 6, figures 7 and 9). The specimen when ground will often split along the lamination plane, thus showing the weakness and imperfect cohesion characterizing these lines. Some of the marine clay on the shore of Lake Melville is without any trace of lamination. The section 6 miles west of Long Point exposes 4 feet of clay without lamination in which subspherical concretions occur. The fine lamination of some of these clays, however, is indicated by the fine elevated lines on such specimens as figures 7 and 9, plate 6.

A noteworthy feature of the Labrador concretions is the large percentage of specimens with an organic nucleus. Concretions with a visible nucleus of any kind are said to be rare in the Pleistocene clays of the Connecticut Valley. Professor Hitchcock states that "In no case in Massachusetts have I seen an organic relic as a nucleus."²⁹ In speaking

²⁹ Edward Hitchcock: Final report on the geology of Massachusetts, 1841, pp. 406-418.

of the same concretions Prof. B. K. Emerson remarks that the "initiating cause entirely eludes our observation."³⁰

The Labrador specimens figured show different species of Pleistocene fossils filling the rôle of nucleus in various stages of envelopment by the concretions.

A remarkable egg-shaped concretion from Alberta, of supposed late Cretaceous age, is shown in plate 6, figures 10 and 11, in order to illustrate another kind of nucleus. This specimen, which in shape recalls the fossil *Struthiolithus* figured by Eastman,³¹ was sent to the Canadian Geological Survey by Mr. C. J. Reach, of Macleod, Alberta, who supposed it to be a fossil egg and reported that it was one of a dozen or more found together. Doctor Wieland, who, at the writer's request, kindly cut the specimen through the longitudinal and transverse axes, found a silicified piece of wood forming the nucleus of this egg-shaped concretion.³²

While shells in many cases, pebbles in some, and roots in others furnish the initial starting point or nucleus of numerous concretions, many of the Labrador specimens show no visible nucleus. Where no visible nucleus is present, what has been the initial stimulant or determinant in the formation of concretions? The segregation of mineral matter at a particular point, however small the amount, might, in the writer's opinion, be expected to serve as the determining factor for the development of a concretion when other favorable conditions were present. The work of Mendel and Bradley³³ and of Herdman and Boyce³⁴ has demonstrated the metal-storing activities of marine mollusks with reference to copper and zinc. They found in some cases as much as 15 per cent of zinc in the ash of the liver of a marine gastropod. Barfurth,³⁵ in his paper on the molluscan liver, pointed out the large calcium and magnesium content of the livers of various gastropods, which varied with the season.

Any soft-bodied marine invertebrate possessing the ability to store in

³⁰ Benj. K. Emerson: Mon. U. S. Geol. Surv., 29, 1898, pp. 711-720.

³¹ C. R. Eastman: On remains of *Struthiolithus chersonensis* from northern China. Bull. Mus. Compar. Zool., Harvard Coll., vol. xxxii, no. 7, August, 1898.

³² Dr. Wieland's view regarding the nature of this very unusual concretion is given in the following extract from a letter to the writer: "I think those Alberta 'duck eggs' may be some uncommonly large development of the '*Feistmantelia*' concretion phenomenon. I have long been noticing lesser forms from small and nearly oolitic to larger and flattened pisolite size in more or less imperfectly silicified trunks. It is to my mind a complex concretionary effect of a very varied expression. But lately Berry has given some figures and a most elaborate account of several of these '*Feistmantelia*' groups of considerable size—nearly an inch long" (Flora of the Cheyenne sandstone of Kansas. U. S. Geol. Surv. Prof. Paper 129, 1, cf. pl. xlvii, 4, 5, 1922).

³³ L. B. Mendel and H. C. Bradley: Experimental studies on the physiology of the mollusks. Am. Jour. Phys., vol. 14, 1905, pp. 314-315.

³⁴ Herdman and Boyce: Report of the Thompson-Yates laboratories, Liverpool, ii, 1899.

³⁵ Barfurth: Archiv für mikroskopische Anatomie, vol. xxii, 1882, p. 473.

its liver a notable quantity of mineral matter would, if buried in sediments, leave no visible trace, but its included mineral matter might furnish a small invisible nucleus for the accumulation of other mineral matter and thus become the nucleus of a concretion. It seems probable that concretions in the Labrador clays and other clays discussed in this paper without any evident nucleus may have started from an inorganic nucleus accumulated in the tissues of a shell-less mollusk which left no recognizable trace in the sediments. This hypothesis must for the present rest on the fact that a great many concretions have formed about definite visible nuclei, which suggests that those without visible nuclei have not begun their growth without some initial determinant. This could have been supplied by the mineral matter left in the sediments by the decay of soft-bodied mollusks.

SLAVE RIVER CONCRETIONS

Concretions have been observed by the writer at only one point in the Quaternary deposits of the Northwest Territories.

Pleistocene clay overlaid by a deposit of sand about 100 feet thick outcrops near Fort Smith, just below the foot of the rapids. The clay at this point contains numerous concretions which show some variety of forms. The dominant form, however, is a compound discoid type comprising a series of regularly graded disks, which give the sides of the concretion a terraced or stair-step aspect. The concretions are not sharply truncated above or below, but have the top and basal sides rounding off gently into dome-shaped surfaces. No organic remains have been found in the clay which furnishes the Slave River concretions, and the concretions are, so far as known, without any visible nuclei. This terraced concretion represents a type of form which has not been observed among the Pleistocene concretions from eastern Canada. The clay outcrop from which they are derived is not sufficiently well exposed to show the laminae which are assumed to be present and to account for the terrace-like divisions seen on the concretions.

The clays furnishing these concretions have been observed only at the Fort Smith locality. The sands which follow above them are apparently without the concretions which characterize similar sands in the Ottawa Valley.

BRITISH COLUMBIA CONCRETIONS

The compound discoid type of concretions is represented by remarkably perfect and beautiful specimens from Quaternary clays at Endako.

British Columbia, which were brought to the writer's notice by Mr. C. J. Kettyle. Mr. Kettyle, who generously collected and presented a collection to the Canadian Geological Survey, later obtained and sent the Survey, at the writer's suggestion, samples of the inclosing marl-like clay³⁶ in which these concretions formed. Four specimens of these concretions are figured on plate 7, figures 3 to 6. Specimen of the inclosing clay sent by Mr. Kettyle show fine lamination, and the superposed disks of which the concretions are composed appear to correspond in thickness with the laminae of the beds in which they formed.

The Slave River concretions contrast with the Endako concretions in the uniformly decreasing size of the disks of the former, each one being, like the units in a pile of scale weights, smaller than the preceding. The disks of the British Columbia concretions in many specimens fluctuate abruptly in size, repeatedly increasing and then decreasing in diameter in the same specimen (plate 7).

In this collection the operation of the forces tending to produce radial symmetry in concretion growth have reached a degree of perfection in the resulting forms which is seldom equaled. The perfect circles represented by the disks of constantly changing size piled one upon another to the number often of one or two dozen show the radial symmetry in a most striking way. In the top-shaped form (plate 7, figures 3-6), with its seventeen disks of sharply contrasted size, the periphery of each is a perfect circle. In other forms which exhibit a regularly changing diameter the peripheries of the cross-sections represent perfect ellipses. In certain other more complicated figures the periphery of some of the sub-discoid elements will take at the two ends of the major axis a "V"-shaped dip, thus preserving perfect symmetry for the particular section involved. In one of these ellipsoidal concretions two wart-like knobs are placed precisely at the ends of the long axis of the elliptic zone to which they belong.

These beautifully symmetrical forms invite some consideration of the probable reasons for their development. On theoretical grounds a completely homogeneous matrix, furnishing conditions in which the physical resistance to concretionary growth is of uniform character and of moderate or minimum strength, should produce concretions with the most perfect symmetry.

No analysis of the inclosing clay has been made, but acid tests indicate a marl-like composition.

³⁶ No analysis has been made, but treatment with HCl indicates a very high percentage of calcium carbonate.

The laminated, very fine-textured sediments in which these concretions have developed afford in texture a close approach to this ideal homogeneous medium for symmetrical concretionary growth within the limits of the individual strata. The planes separating these layers mark the vertical limits of the complete homogeneity which characterizes each stratum and produce discoid forms instead of the spheres which a clay homogeneous both vertically and horizontally would produce. The fine lamination of the clay interrupts in a degree its homogeneity. This interruption coincides with a series of horizontal planes corresponding to the boundaries between the laminae. Between the limits of any two of these planes the homogeneity is perfect or nearly so and results in the discoid or subdiscoid symmetry of the several units in the forms represented by figures 3 to 6, plate 7. Slight differences in the composition of the different laminae which supplied the material for the several disks of a concretion, contrasts in the degree of water saturation of the several laminae concerned in the growth of a given concretion, and variations in the ground water level were probably all factors in the development of the compound discoid forms, which are composed of a series of disks varying greatly in size.

Dr. George Hanson has furnished, at the writer's suggestion, the following notes on the field relations of the Endako concretions:

"The concretions are found on the banks of a small creek about 1 mile west of Endako, British Columbia. Clay banks containing concretions are known to extend for about one-half mile along the creek. Small landslides have exposed the clay in several places. The banks are nowhere more than 50 feet above the bed of the creek and the surrounding country is flat or rolling. Going north from the railway along the creek, the first slide reached exposes stratified clays and sandy clays. The second, third, and fourth slides are reached at intervals of 200, 300, and 500 yards and all consist of similar material.

"As seen from the railway, the country appears to be of very low relief for 75 miles west and for 100 miles east of Endako. The rocks seen are chiefly boulder clay and other morainal material. Stratified clays are occasionally seen. The clays at Endako are horizontal and are very well stratified. They are not overlain by any glacial material. The base is unexposed, but glacial deposits are inferred from the abundance of boulder clay in the vicinity. The clays are probably of late Pleistocene or early Recent age.

"The strata in the Endako clays vary from paper-thin laminae to 8-inch beds. The sandy clays and sands are commonly in 1 to 4 inch bands.

"There is a marked gradation in the shape of the concretions in a north-south line. The most southerly slide contains flat disks, flat ovals, and numerous irregular branching flat concretions. In the second slide the concretions are more regular. The fourth slide contains a few irregular concretions and all the good chessman type of concretions. None of the perfect ones were

seen in place, but some were found in the clay. The clay oozes or creeps down to the creek and is here washed, leaving a placer of concretions.

"The concretions have commonly one flat side and a side opposite to it with a convex curvature. In some instances the flat side is uppermost; in other cases it is down. The greatest diameter of the flat concretions is parallel to the strata. Concretions with a vertical length exceeding the transverse length consists of superposed disks which lie parallel to the strata. Sandy beds seem to be the most favorable for concretions. The flat side of the concretions lies in a thin layer of sand and the convex side is in clay or sandy clay. This was observed in several places.

"Quite a number of beds in a clayey bank contain concretions, but they are concentrated along certain beds and are not scattered promiscuously throughout the clay. A plane 1 foot square along a concretion-bearing bed might have half its area occupied by concretions. A vertical plane 1 foot square might cut concretions only in a certain bed. Further, the concretions are concentrated in areas along any particular concretion-bearing bed. An area of 50 square feet along a concretion-bearing bed might contain 25 square feet of irregular concretions. An adjacent area of the same size along the same bed might contain only a few square inches of concretion per square foot of area."

The contrasts noted by Doctor Hanson in the shape of the concretions found at the four localities mentioned probably correspond to lithologic differences in the clays at slightly different levels.

OTTAWA VALLEY CONCRETIONS

GENERAL STATEMENT

The Pleistocene concretions from the lower clays in the Ottawa and Saint Lawrence valleys differ from those of the Connecticut Valley, which are barren, in inclosing fossils very frequently. This has caused the Greens Creek concretions, which have been briefly described by Weston,³⁷ to become rather widely known. Dawson³⁸ has described and listed many of their fossils and incidentally referred to the inclosing nodules. Dr. H. M. Ami has collected from these concretions a considerable fauna, including insects and plants as well as the common invertebrates. Johnson³⁹ has discussed one of the types of concretions found in the Ottawa Valley Pleistocene clays.

Pleistocene deposits in the Ottawa Valley have a vertical range of about 600 feet, according to Johnson.⁴⁰ The basal 100 feet, however, lie below the level of the Ottawa River, so that nothing is known of the con-

³⁷ T. C. Weston: Notes on concretions found in Canadian rocks. Trans. Nova Scotian Inst. of Sci., vol. ix. pp. 1-9, session 1894-1895.

³⁸ J. W. Dawson: The Canadian ice age, 1896, pp. 266-267.

³⁹ W. A. Johnson: Pleistocene and recent deposits in the vicinity of Ottawa. Mem. Can. Geol. Surv., no. 101, 1917, p. 29.

⁴⁰ Op. cit., p. 20.

cretions of this part of the section, if any exist. Above 340 feet above tide these deposits are of very limited extent and not known to contain concretions. The beds to be considered in the following pages have therefore a thickness of only about 225 feet. A generalized section of these beds as seen between Rideau Junction and the mouth of Greens Creek is shown below:

RIDEAU RIVER AND GREENS CREEK SECTION

	Feet
Sand with some intercalated silty clay in lower part, containing <i>Mytilus edulus</i> and <i>Saxicava</i>	65
Clay, free from sand, finely laminated.....	20±
Silty blue-gray clay with red or brownish bands and numerous fossils..	65±
Fine blue clay with <i>Mallotus villosus</i> , <i>Portlandica arctica</i> , etcetera....	75±
Total.....	225

The difference between the three divisions recognized in the clays of this section are not of the magnitude or obvious character which usually distinguish formations or even members of a formation. There are, however, differences which brick-makers recognize and which the contrasts between the concretions found in them show to be real ones.

Each of the four sets of beds recognized in the section is characterized by concretions possessing certain group or family resemblances which serve to separate them into easily recognizable groups corresponding to the inclosing sediments in spite of their diverse features (figure 1).

Mrs. J. M. Arms Sheldon found in her study of the Connecticut River concretions that "each bed has a form of concretion peculiar to itself. You would never, for instance, find a circular disk and a cylindrical clay-stone imbedded together."⁴¹ Essentially the same general statement can be made concerning the Ottawa Pleistocene concretions and the sediments holding them. It is proposed here to point out certain contrasts between the concretions of the several beds of the marine clays, the non-marine clays, and the sands at the top of the series.

CONCRETIONS OF THE LOWER CLAYS

The concretions of the lower division of this series (number 1) fall into two general classes with reference to the symmetry which they exhibit. The most abundant concretions are those which approach more or less closely the spheroidal type of symmetry. The most perfect of these show a spheroidal form, which is nearly always greatly depressed, the vertical being very much shorter than the horizontal axis and at right

⁴¹ J. M. Arms: Can. Rec. Sci., vol. 4, 1891, p. 238.

angles to the bedding of the clay. The concretions occurring at this horizon show a large variety of forms. The majority of concretions with-

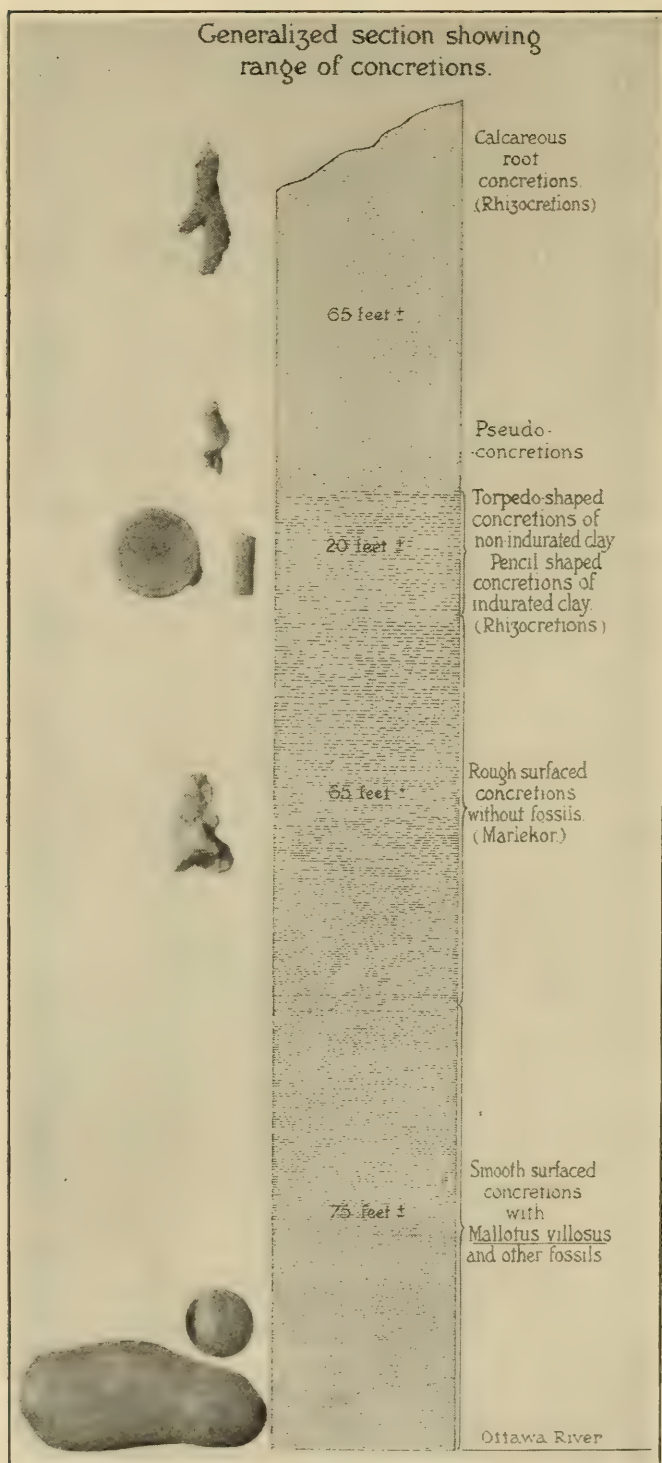


FIGURE 1.—Generalized Ottawa Pleistocene Section

Showing the types of concretions characterizing different parts of the section. Concretions are about one-fourth natural size.

out radial symmetry about a vertical axis have a plane of symmetry parallel to the bedding of the clays and never vertical to it. Concretions 3 to 6 inches long, which frequently inclose the skeleton of a small fish of similar length as a nucleus, are common among the concretions of the latter type. In these concretions the shape of the outline is controlled entirely by the shape of the fossil (plate 8). These fish-inclosing concretions have long been known and may be seen in various museum collections. *Mallothus villosus* is the fish generally found in them. Frequently two or more fish skeletons lying at various angles to each other give these concretions a highly irregular shape (plate 8, figures 3, 4). The Survey collection of these concretions includes one specimen which incloses the skull and a portion of the spinal column of a marten (*Martes americana americana* Turston) (plate 8, figures 1, 2). The flat-

tish type of concretions present many erratic shapes, some of which have numerous sharp-pointed extensions. Forms with lateral extensions terminating in sharp points, the flattened doughnut type, and various other irregular shapes generally show a certain amount of symmetry with reference to a plane midway between the upper and lower sides. The irregular shape of such concretions is probably due to slight different degrees of resistance to their growth in horizontal directions, growth taking in such cases always the line of least resistance. This resistance, if we may judge from the symmetry of the concretions, has varied but little in the vertical direction, but greatly in the horizontal direction. Many concretions have their symmetry interrupted through attachment to or partial inclosure of a fossil shell or pebble. In such cases the attached shell or pebble has probably served as the nucleus or starting point of the concretion, but conditions of growth have been more favorable on one side of the nucleus than on others, thus leaving the pebble or shell nucleus on the periphery instead of at the center of the concretion, where it is often found (plate 10, figure 7). The rough surface shown by figures 6 and 8, plate 10, is the result of the clay which adheres to the concretions when removed from the original bed. Weathering leaves such surfaces entirely smooth. Specimens occur but rather rarely in which the concretionary growth has centered about a very angular rock. A highly angular piece of limestone serves as the nucleus of the concretionary growth shown in plate 9. In other cases small shells are found on the periphery of greatly depressed oblate spheroids, whose position suggests that their inclusion within the limits of the concretion has been a purely accidental matter, resulting from their having been within the limits of the increasing radius of the growing concretion (plate 6, figure 3). In such cases the true nucleus may be of the type suggested in discussing Labrador concretions.

In spite of the great diversity in form shown by the concretions of this class, which may be designated as claystones, they show, with very few exceptions, some form of symmetry or an approach to symmetry, and always the surface of weathered specimens exhibits a more or less regular curvature. These two characteristics distinguish them quite clearly from the concretions of the second group of sediments in the Pleistocene deposits of the Ottawa Valley.

One of the most interesting and significant features connected with the Pleistocene concretions is seen in their distribution. The distribution of the concretions of the lower clays and of the other divisions to be considered are all sharply localized. Concretions may be found sparingly or rather rarely at most places along the rivers and creeks in the lower marine clay, but they occur abundantly at only a few places. In sharp

contrast with the occurrence of concretions along the Ottawa River and some other streams abundantly or sparingly, according to the location, is their absence or scarcity in the same clays where cut by ditches. The general absence of concretions from the clays cut by ditches leads to the inference that their development is limited to a superficial zone of clay which has been exposed for a considerable period in the stream-bank sections of the district. This conclusion, it may be noted, is in harmony with the view now generally accepted that the silicification of fossils is ordinarily a wholly superficial phenomenon which takes place but a very slight distance below the surface of the limestone in which the fossils are embedded,⁴² Professor Hughes⁴³ likewise found the beekites to be superficial in their occurrence, being absent where "the limestone fragments were not decomposed."

Concretions occur abundantly at only a few localities along the streams. Careful search of the clay banks along the Ottawa River above Greens Creek will seldom disclose more than one or two concretions within the limit of a hundred yards. In the same clays immediately below Greens Creek for a distance of half a mile or more many hundreds of concretions may be seen within the same distance limits. No other locality near Ottawa or elsewhere is known where the abundance of concretions approaches that observed along the half mile of river bank between Greens Creek and Besserers Landing. Since the peculiar distribution of concretions at the mouth of Greens Creek appears to give a clue to an important factor in the formation of the concretions of the clay cut by this stream, their distribution at this point will be stated in some detail. Greens Creek has a width of about 50 feet at the mouth and enters the Ottawa River 6 miles below Ottawa. A careful search of the clay bank on the east side of the creek was made for 200 yards above the mouth without finding a single concretion. Immediately below the junction of the creek and river concretions are abundant and along the river bank near the low-water stage will average probably five to the square foot.

The clay exposed in the bank of the river and the bank of the creek is of precisely the same physical character and the same thickness. The mingling of the water of the creek and river may be one of the factors responsible for the relative abundance of concretions in the river bank below Greens Creek. Since the concretions are wanting or scarce where the clay is exposed to either creek water or river water alone and very abundant where both river and creek water may lave the bank, it is diffi-

⁴² Henry Nettleroth: Kentucky fossil shells. *Ken. Geol. Surv.*, 1889, p. 120.

⁴³ T. M. McKenney Hughes: *Mineralogical Mag.*, vol. viii, no. 40, 1889, p. 266.

cult to escape this conclusion. It is hardly probable, however, that the contrast between the chemical composition of the river and creek waters is the active factor in causing the scarcity in one area and abundance in the other. A more potent cause is believed to be the difference in temperature between creek and river waters. The two kinds of water contrast strongly in temperature except during the winter, when both streams are sealed by ice. The lakes through which the Ottawa flows, as well as its northern sources and greater depth, make its waters much colder throughout the summer than those of Greens Creek. Thermometer readings were made to test the amount of these differences on August 15, with the results shown below:

Surface temperature in Ottawa River near Greens Creek.....	72°-73°
Surface temperature in mouth of Greens Creek.....	78°-80°

The contrast in temperature between the water of the creek and river in early spring is considerably greater than the summer contrast, as the following figures, which were taken April 28, show:

Temperature of water of Ottawa River.....	34°
Temperature of water, mouth of Greens Creek.....	54°
Air temperature over river.....	46°
Air temperature over creek noticeably higher, but not measured.....	...

The water of the Ottawa is derived largely from northern sources, and for a considerable portion of the early spring its waters are notably colder than those of small streams from the south like Greens Creek. The outflow of the waters of a relatively small stream of warm water into a river with much colder water results in frequent fluctuations in the temperature of the water in contact with the bank below the creek mouth. Whether the creek temperature or the river temperature will dominate the narrow zone adjacent to the shore will depend on the relative stages of water in the two streams as well as the strength and direction of the wind at different times. There will be periods when the influence of the creek will be blotted out by high water in the river, and *vice versa*. These changes of temperature will be transmitted to the ground-waters permeating the clays of the river bank and result in frequent and abrupt changes in the lime-solvent powers of these waters by affecting their CO₂ content through increasing or lowering the temperature. Changes of this character, it is believed, would stimulate the development of concretions.

Another factor in the control of conditions favorable to the formation of these concretions is the diurnal change of temperature. River and creek bank sections partially or completely protected from the sun by

forests would experience a small daily change in temperature, and accordingly small loss of water by evaporation, as compared with sections exposed to the full glare of the sun where the banks are denuded of forests. This complete exposure to the sun would mean relatively rapid movement of ground-water toward the exposed section as a result of evaporation and a consequent large transfer of the soluble materials required for the growth of concretions into the superficial vertical zone represented by the face of the section.

CONCRETIONS OF THE UPPER CLAYS

In the silty clays which follow, the lower fine-textured marine clay concretions are, at some localities, abundant. These beds afford concretions quite unlike the claystones of the lower clays, but which are similar to, if not identical with, the Norwegian forms called by Kjerulf⁴⁴ and other Scandinavian geologists *marlekor*. A distinctive term is needed for these forms, and it is considered desirable to designate them by the Scandinavian name *marlekor*, which means fairy stones, a usage already introduced by Quirke.⁴⁵

These concretions are characterized by a highly irregular or warty surface and generally show no approach to any type of symmetry, a feature in which they contrast sharply with the concretions just described. Instead of the usual smooth, more or less regular surface curvature of the claystones from the lower clay, these forms show innumerable abrupt irregularities in the surface, including pits and depressed groove-like lines pursuing entirely erratic courses (plate 10, figures 2-5). The spherical or subspherical type of concretion does not occur in association with this type of concretion. These frequently show, on breaking, small shrinkage cracks, which may or may not extend to the surface (plate 10, figures 2 and 5). No example of these concretions is known showing a shell or other organic nucleus. In size they range from the dimensions of a pea to a man's fist.

This type of concretion may be seen in the upper clays at various localities. Specimens of these concretions occur sparingly in the road-side cuttings in the clays about 2 miles south of Wilsons Corners, Quebec. They occur at various localities in the district and are abundant in the lower portion of the brick-clay pits southwest of Billings Bridge.

Their distribution in these clay pits is confined to the northern margin of the lower pit in beds which are between 5 and 15 feet of the original

⁴⁴ Op. cit., pl. 5.

⁴⁵ T. T. Quirke: Can. Geol. Surv. Mem. 102, 1917, p. 56, pl. 5.

surface of the hill slope. Workmen with many years of experience in these pits report never having seen them in the clays which have been at a much greater depth nor in the clays of the upper pit, which are less silty. This distribution the writer's own observations appear to confirm. The relation of these concretions to the inclosing clays is indicated in plate 10, figures 2-5. The limitation of these concretions to beds within a few feet of the surface indicates that their development occurs in the path of waters moving down the surface slope and in the superficial zone just below the surface, where fluctuations of temperature and water supply are greatest. Concretions are most abundant within or near the zone which is subject to freezing and thawing during one-half of the year and alternate desiccation and soaking by rains throughout the other half. The stimulation of the movement of ground-water resulting from these climatic agencies is doubtless the most potent factor in the formation of the hard rugose claystones of these beds.

Quirke, in describing this type of concretion from the Pleistocene clay of the Espanola district, Ontario, states that he does not consider them true concretions, but "rather to be the indurated remains of the viscous fluid, which was covered by fine materials."⁴⁶ Hardened clay pebbles are formed in abundance along the banks of the Ottawa River and may be preserved for a considerable period, but none of the hundreds of such pebbles which the writer has examined shows any of the peculiar markings and erratic incised lines on their surface found on the concretions of these upper clays and shown also in Quirke's illustrations. These peculiar features the writer considers characteristic of this class of concretions and impossible of formation and preservation on dried clay pebbles.

Associated with these *marlekor* or rough-surfaced forms another kind of concretion occurs, if this term may be applied to the slightly indurated cylinders of clay which mark the course of many small tree roots which penetrate these beds. The difference in both hardness and composition between these and the inclosing clay is very slight. A color contrast, due presumably to a trace of iron, clearly outlines these structures, which may be considered a preliminary or antecedent phase of one type of cylindrical concretion in which an organic agent serves as the original stimulus to development (plate 11, figures 11, 12).

The higher clay beds at the Billings Bridge brick-clay pits, the O'Reilly pits, and elsewhere show still another type of non-indurated concretion in which the hardness, though greater in some cases, differs little, if any,

⁴⁶ T. T. Quirke: Can. Geol. Surv. Mem. 102, 1917, p. 56.

in others from that of the surrounding clay. The central axis of these structures is marked by a straight tubular canal generally a millimeter or less in diameter, which evidently occupies the position of the small rootlet, which was the determining element in the formation of these incipient concretions. These forms are due to very small rootlets following approximately a horizontal direction, while those just described have developed about roots traversing the beds in a vertical direction.

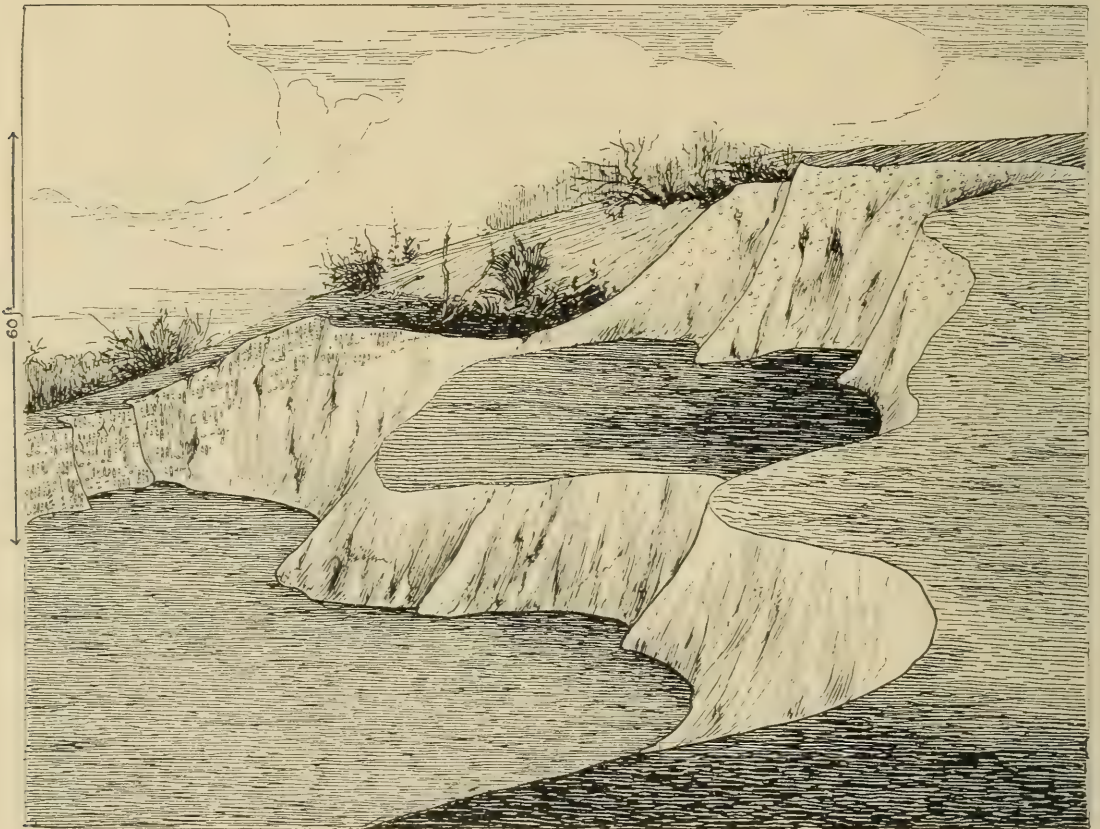


FIGURE 2.—Sketch showing two Levels of clay Pits southwest of Billings Bridge

Each level carries a distinct type of concretion. The pencil-shaped root concretions (plate 11, figures 11, 12) and the *marlekor* (plate 10, figures 2-5) are confined to the lower level, and the non-indurated concretions (plate 11, figures 13, 14) to the upper level.

Although without differentiating hardness, they show a beautifully symmetrical structure, which is often apparent to the eye only through the concentric layers of lemon and pale brown which define the several zones of slightly different composition developed by concretionary growth. These concretions differ from the root concretions already described and another type to be mentioned later in their bulging barrel-shaped sides and torpedo-shaped ends. They lack the considerable length, often amounting to 1 or more feet, shown by the root concretions, and have

their long axis only two or three times greater than the transverse axis and generally approximately parallel to or forming a slight angle with the bedding planes instead of traversing them at right angles, as the ordinary root concretions do. These structures, which are seldom more than 3 or 4 inches in length, clearly represent an early stage of concretionary growth, which, like that of the cylindrical form just described, is doubtless in progress at the present time. The specimens figured were collected by W. A. Johnston, who first brought this structure to the writer's notice. Continued development might be expected to produce from them forms resembling certain subcylindrical cryptozoons. The stratigraphic relations of the concretions of the upper clays are shown in figure 2.

PLEISTOCENE SAND AND SHELL CONCRETIONS

A fourth type of concretion which occurs only at certain localities in the upper or superficial layers of the Pleistocene sands has the shape roughly of a small slender icicle and stands vertically in the beds holding it. A small root or the cavity left by its decay invariably traverses the center of these root-like concretions. The concretions have no resemblance in form to those found in the lower beds. Their general shape and contour is controlled very definitely by the root nucleus. In composition they are largely carbonate of lime, which has cemented together the sand adjacent to the root nucleus. The degree of induration exhibited by them varies greatly, some specimens crumbling almost as easily as the adjacent sand. Others have a firmness approaching that of limestone, while some specimens show a very perfect cementation of the sand and the hardness of flint.

The distribution of the icicle or root shaped concretions in the superficial beds of the Pleistocene sands is likewise confined to a few localities where conditions were especially favorable to their formation. One of these localities is the upper slope of the sand terrace at the sand pits near Rideau Junction (figure 3). They also occur in extraordinary abundance in the fine-grained sandy beds on the shore of Lake Ontario opposite the Presqu'île summer hotel (plate 11, figures 1-4). They may be seen at various other localities in the Pleistocene sands of Ontario.

It appears obvious that the small rootlets found in the center of the icicle-shaped concretions of the Pleistocene sands have been the initial factor in their formation. It will hardly be questioned that the small roots frequently found in the center of these concretions through the development of humous acids have led to the segregation of the calcareous constituents of the sands in which they were growing, thus leading to

their development through lateral deposit of calcium carbonate around the roots.

The calcareous root concretions appear to have developed only around dead roots. Examination of a great many roots in the beds where these concretions are found has failed to show a single example of the calcareous tube inclosing a living root.

By way of illustrating further the influence of roots in causing the lithification of unconsolidated sediments surrounding them, two specimens from the Pleistocene shell beds at Saint Augustine, Florida, have been included in the plates (plate 12). In the island east of Saint Au-



FIGURE 3.—*Calcareous root Concretions exposed by wind Erosion*

gustine extensive beds of unconsolidated sea-shells occur a few feet above the tide, which are occasionally traversed by irregular finger-like masses of consolidated coquina extending down through the unconsolidated shell beds. These irregular masses of cemented shells extending across the bedding are invariably found to inclose a root which has evidently been the active factor in causing the cementation of the shells within the limits of a narrow zone surrounding it (plate 12, figure 1). Sometimes these show a button-like effect, owing to lithification having extended farther into the loose shells in some strata than in others from the root center. The root nucleus of these coquina structures are generally in a very good state of preservation.

Dr. J. I. Northrop⁴⁷ applied to the root-induced structures described above the term *rhizomorphs*. This name was applied by Northrop to designate cylindrical root-like masses of limestone in the Bahama Islands concentrically arranged about a tubular axis "formerly occupied by plant roots and rootlets." These Bahaman structures differ from those just described in representing only lithification of the calcareous sand or very soft limestone, while the Pleistocene sand structures represent segregation as well as induration of the material composing them. Northrop, however, made this term embrace a variety of tubular structures, including the tubular ferruginous masses found in the New Jersey clays and elsewhere.

Todd used at an earlier date the term *incretions* for the same class of structures included by Northrop's *rhizomorphs*. Since the name *incretion* implies a particular method of growth which may not entirely coincide with the facts, a name which refers to the shape of the structures alone appears preferable. There is certainly need of a general term for the class of concretions having the distinctive features characterizing the pipe-like clay and calcareo-siliceous concretions. The term *rhizomorph* which Northrop proposed for these structures is not available, because it has been previously used by the botanists. The preemption of this name by botanical technology leads the writer to suggest as a substitute for it the term *rhizocretion*. This term may conveniently be made to include concretions having a root-like shape or having had a root as a nucleus.

In the lower part of the sand beds the calcareous root concretions are found in certain localities associated with vast numbers of hardened clay fillings or casts of tubular cavities of highly irregular shape with a vertical trend. These tubular clay casts, many of which approach roughly the corkscrew shape, remind one somewhat of Barbour's⁴⁸ "*Dæmonelix* cigars or fingers," although they are more slender and lack the blunt rounded ends of the "cigars." The sand beds holding these curious clay casts lie directly above beds of clay of the same type as that found in the tubular clay casts. The extraordinary irregularity in shape of these clay fillings of the vertical tubular openings into which they have been forced is the most puzzling feature which they present. These irregular clay structures change abruptly from a semi-columnar to a semi-spiral form and frequently bifurcate into fine and coarse branches. Frequently needle-like perforations often filled by the roots which made them traverse longitudinally these clay structures. These structures are not

⁴⁷ J. I. Northrop: *A Naturalist in the Bahamas*, 1910, p. 40.

⁴⁸ *Bull. Geol. Soc. Am.*, vol. 8, 1897, pl. 34.

indurated in any degree and remain as soft as the clay in the beds below the sand from which they were derived. The stratigraphic relations of these structures to the clays and the sands are shown in figure 4.

The origin of these highly irregular-shaped fillings affords an interesting problem. The sand beds associated with them are traversed by numerous burrows of insects or worms which now live in these beds. These tubes of recent origin are, however, invariably circular in cross-section and without clay fillings, while the clay fillings show in most

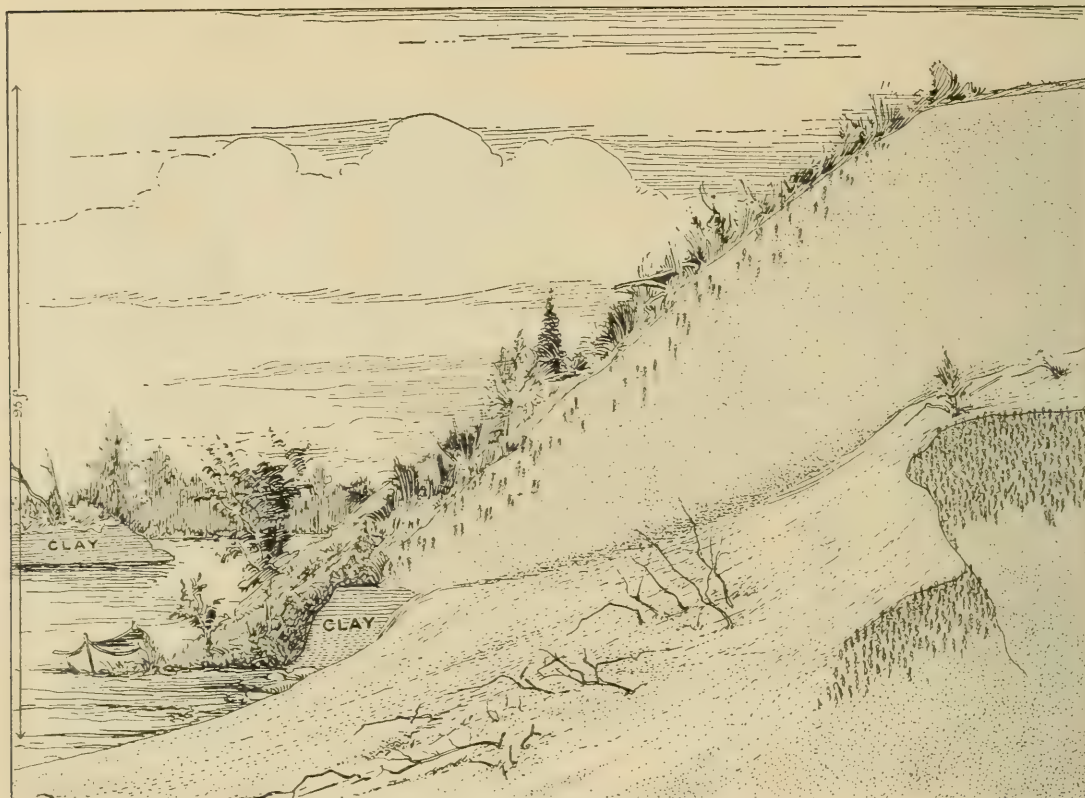


FIGURE 4.—*Sketch at Rideau Junction, Ontario*

Showing relations of sand and underlying clay, together with the occurrence of calcareous root concretions (plate 11, figures 1-4), along the slope of the sand bank and the pseudoconcretions near base of sand beds in lower right-hand corner.

cross-sections a wide divergence from a circular outline. Since none of the many insect or worm burrows of recent origin present the extraordinary shape of these clay-filled perforations of the sand beds, the latter do not appear to have been formed under conditions now existing. If, however, we go back to the conditions which existed shortly after the lower part of the sand beds were laid down, the probable conditions of their origin can be inferred. Marine animals of various species may then have been accustomed to burrow through the sand to the clay.

Saxicava arctica, for example, drives straight burrows deeply into the sand and they may still be found abundantly in them near the structures described. The filling of these burrows by the still semi-fluid blue sea-ooze under sand pressure might result or they might have been filled by the animals constructing them.

The burrowing habits ascribed to *Balanoglossus*, a soft, worm-like marine animal belonging to the phylum Chordata which is common along parts of the Atlantic coast, might suggest that a representative of this genus or some other creature of similar habits produced the clay-filled burrows of the Pleistocene sands at Rideau Junction. The following notes on the burrows of *Balanoglossus* by Alice R. Northrop⁴⁹ refer to a species found in the Bahama Islands:

"Followed one of the holes down straight about 10 inches, then along in a spiral for about 18 inches to the rock, where I found a *Balanoglossus*. Followed two more holes, but lost them before reaching the animal. When found, the whole animal is surrounded by a transparent gelatinous coating. Laid one on paper; when extended, it is 12 inches in length. Some were over 2 feet long."

The noteworthy features of this description of *Balanoglossus* and its burrow, with reference to fossil burrows, are the combination of direct and spiral courses shown in the same burrow. The contrasted types of spiral and straight burrows are characteristic of some of the clay tubes at Rideau Junction. The power of strong contraction possessed by a worm-like body 1 or 2 feet in length, if exercised within a burrow in soft sand, would be very likely to give rise to great irregularities in the size and shape of the burrow. Deposits of slime and mucus like those ascribed to *Balanoglossus* would doubtless still further accentuate such irregularities. Some marine creature producing burrows comparable with that of *Balanoglossus* seems more likely than the straight boring *Saxicava* to have formed the curious irregular-shaped clay-filled burrows at the Rideau Junction sand pits. These structures belong in the class of fossil burrows or pseudoconcretions.

SUMMARY

The concretions described in this paper belong to well defined types characterized by physical features which can be readily discriminated. The areal distribution and geological range of these types are determined (1) by the presence or absence of the lithologic features essential to their

⁴⁹ J. I. Northrop: A Naturalist in the Bahamas, p. 5. Columbia Univ. Press, 1910.

development and (2) by the occurrence of certain local conditions essential to their formation.

These types include the compound discoid forms found in British Columbia and on the Slave River in the Northwest Territories, which are unknown in eastern Canada. The claystones of the lower clays in the Ottawa Valley and eastern Labrador belong to another type characterized by a great variety of form, but showing a generic resemblance in the smooth surface which is always present and the approach to symmetry which these concretions exhibit. A third type, which has been designated as *marlekor*, contrasts sharply with the approximately symmetrical smooth-surfaced claystones. The *marlekor* are distinctly unsymmetrical and possess a highly irregular surface and internal features never found in the claystones. When found in the same district, the *marlekor* occur above the claystones in the area studied.

Another group of concretions, with only a slight resemblance to the preceding, are grouped under the class name of rhizoconcretions. These comprise three distinct varieties of concretions, each of which has a root for a nucleus. One of these is confined to the sands which lie at the top of the Ottawa Valley Pleistocene section. Another variety is confined to the upper clay beds of the same section. The third is found in the upper part of the beds in which the *marlekor* occur. None of these rhizoconcretions is known in the lower clays of the section in which the claystones are so abundant.

Certain irregular-shaped, slender, vertical structures of soft clay penetrating a sand formation are described as pseudoconcretions. These occur in the Ottawa section and are considered to be clay-filled burrows of marine animals.

Some of the concretions discussed in this paper are known to be confined to the superficial portions of the beds in which they occur. All of them are probably limited to those parts of the formation containing them which lie relatively near the surface.

Calcium carbonate or other mineral matter separated from the seawater and segregated in the sediments by the decay of soft-bodied marine invertebrates may have supplied nuclei in many cases for concretions without visible nuclei.

DISCUSSION

Prof. T. T. QUIRKE: Certain surficial features on *marlekor* look like welts or small, raised ridges. They may have been caused by the filling of shrinkage cracks by hardened material, followed by continued shrinkage of the main mass. Other concretion-like masses appear to have been

formed by the rolling of mud balls down clay slopes, with the result that they carry on their surfaces a sort of wrapping of clay layers about the central parts.

Author's reply: Professor Quirke's observations on *marlekor* have been made in an area somewhat remote from the one in which my own studies were made, and it is possible that some of the specimens referred to by him may have a different genetic history from that of the *marlekor* of the Ottawa district. I am not prepared to explain just how the fissures in the interior of the *marlekor* originated, but the clay pebbles which may be seen in abundance along the Ottawa River in late summer certainly show no such features; neither do any of the mud balls which have come under my notice along the Bay of Fundy estuaries possess any features which suggest in any way a comparable origin for the *marlekor*. The best evidence, perhaps, that the *marlekor* were produced by the same general agencies which are responsible for the claystones occurring at a lower level in the clays, is found in the fact that, like them, they are confined to that portion of the clays which lies within a few feet of the surface.

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EXPLANATION OF PLATES

PLATE 5.—*Concretions*

- FIGURE 1.—Concretion of cemented sand and fine gravel, Kenemich River, Labrador.
- FIGURES 2 and 3.—Concretions attached to pebbles, Kenemich River, Labrador.
- FIGURES 4-8.—Concretions of irregular shape with thin outer shell of ferruginous material. Hamilton River, Labrador, 7 miles above mouth.
- FIGURE 9.—Subspherical concretion with outer shell of non-indurated material, Kenemich River, Labrador.
- FIGURES 10 and 11.—Concretions with median constriction, south side Lake Melville, Labrador.
- FIGURE 12.—Concretion with constrictions, south side Lake Melville.

PLATE 6.—*Concretions*

- FIGURES 1 and 2.—View of the two halves of a concretion showing the shell of a *Yoldia* as the nucleus.
- FIGURE 3.—Concretion with a marine shell attached to the surface, Kenemich River, Labrador.
- FIGURES 4 and 5.—Concretions with shells partially inclosed, Kenemich River, Labrador.
- FIGURES 6, 7, and 9.—Concretions with thread-like ridges corresponding to the lamination of the clays in which they were formed, Kenemich River, Labrador.
- FIGURE 8.—Concretion with iron-stained surface, Kenemich River, Labrador.
- FIGURES 10 and 11.—Views of the two halves of an egg-shaped concretion from Macleod, Alberta. Figure 10 shows a piece of fossil wood acting as the nucleus, while figure 11 indicates the external appearance of the opposite half.

PLATE 7.—*Concretions*

- FIGURES 1 and 2.—Side and top views of terraced or discoid concretions, Fort Smith, Alberta.
- FIGURES 3-6.—Compound discoid concretions, Endako, British Columbia.

PLATE 8.—*Concretions*

About two-fifths natural size.

- FIGURES 1 and 2.—Opposite sides of a concretion showing skull and other parts of the skeleton of a marten, Ottawa River below Greens Creek.
- FIGURES 3 and 4.—Concretion showing parts of three skeletons of *Mallotus villosus*.

PLATE 9.—*Concretions*

About one-half natural size.

FIGURES 1 and 2.—Two views of an angular piece of limestone partially covered by a concretionary growth. A cross-section of the specimen made by breaking is shown in figure 1 and a side view of the opposite end by figure 2.

PLATE 10.—*Concretions*

FIGURE 1.—This doughnut-shaped concretion shows the smooth surface characteristic of the slightly weathered "claystones" of the Lower Pleistocene clay of the Ottawa Valley.

FIGURES 2-5.—These concretions represent the type to which the term *marlekor* will be confined. Note the shrinkage cracks shown by figure 2 and figure 5; also the irregular surface displayed by all of them. From the middle division of the Pleistocene clays south of Wilsons Corners 3 miles, Province of Quebec.

FIGURES 6 and 8.—These specimens show the thin shell of partially indurated clay which adheres to the concretions when removed from the bed in which formed, Ottawa River below Greens Creek.

FIGURE 7.—Concretion attached to the side of a pebble, lower clay, Ottawa River below Greens Creek.

PLATE 11.—*Concretions*

Seven-eighths natural size.

FIGURES 1-4.—Root concretions composed of sand cemented by calcium carbonate. Specimen number 2 has been ground to show the channel originally filled by the root. From the sand beds at Rideau Junction, Ontario.

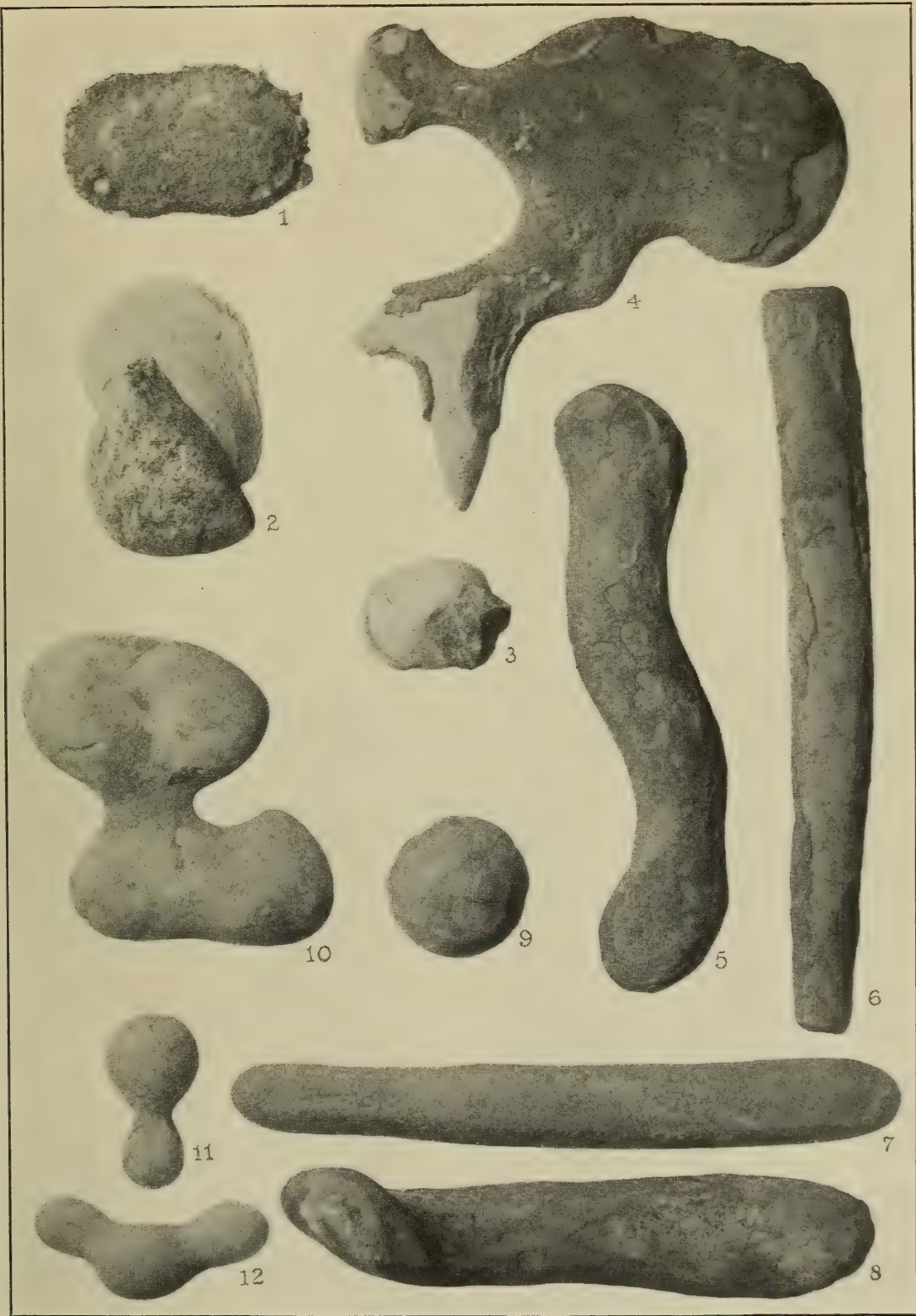
FIGURES 5-10.—Pseudoconcretions composed of soft blue clay filling irregular-shaped vertical tubes in the sand beds, Rideau Junction, Ontario.

FIGURES 11 and 12.—Side and cross-section of a root-shaped concretion consisting of indurated clay, brick clay pits southwest of Billings Bridge one-half mile.

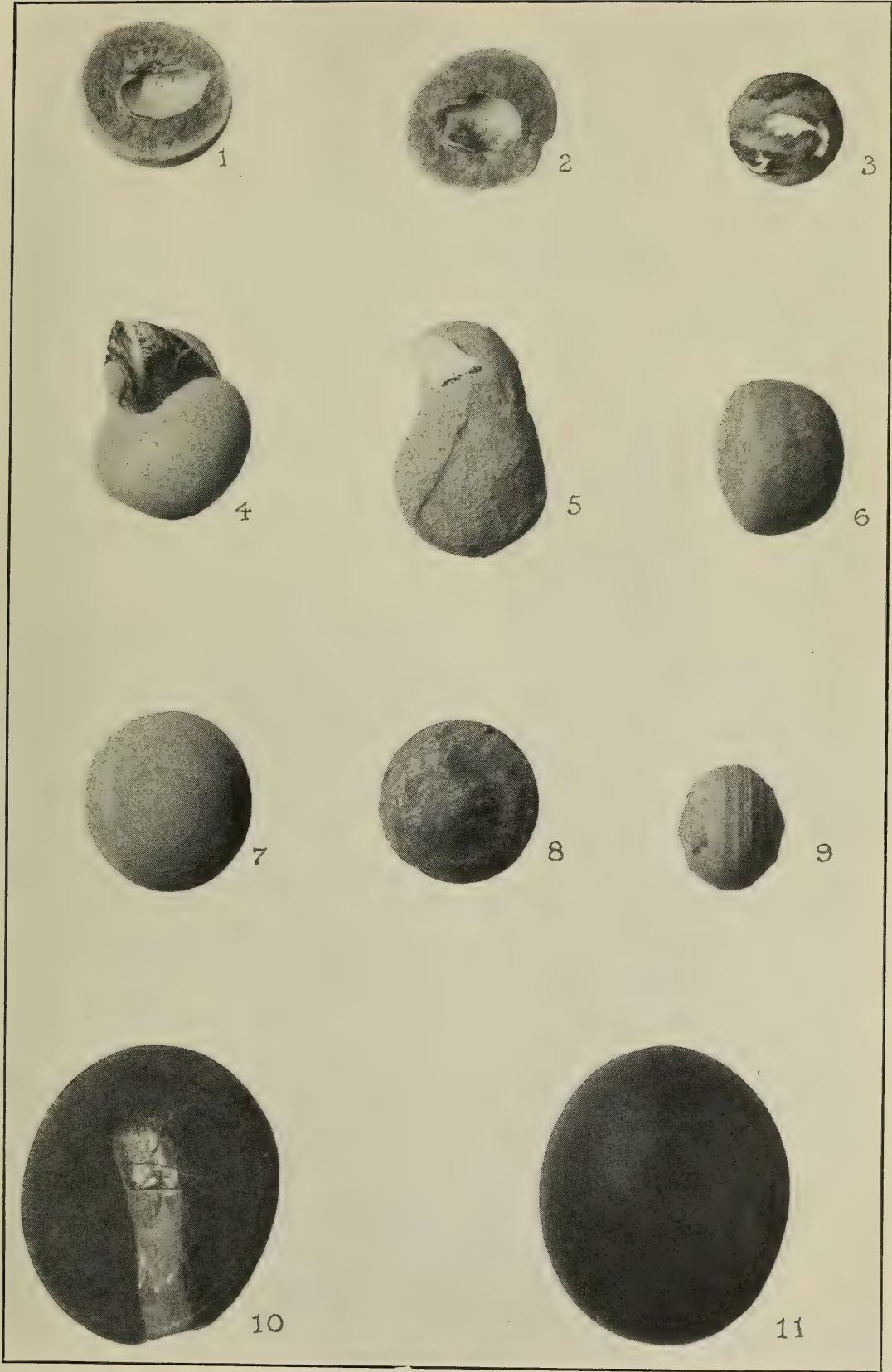
FIGURES 13 and 14.—Soft or very slightly indurated concretions with a root nucleus. Figure 13 is a ground specimen showing the concentric orange-brown colored zones which surround the axis. Upper clay beds southwest of Billings Bridge, Ottawa, one-half mile.

PLATE 12.—*Concretions*

FIGURES 1 and 2.—Concretions (rhizoconcretions) formed in a bed of unconsolidated shells by calcium carbonate cementation of shells adjacent to roots. Note the root nucleus in figure 1. Pleistocene beds, Saint Augustine, Florida.



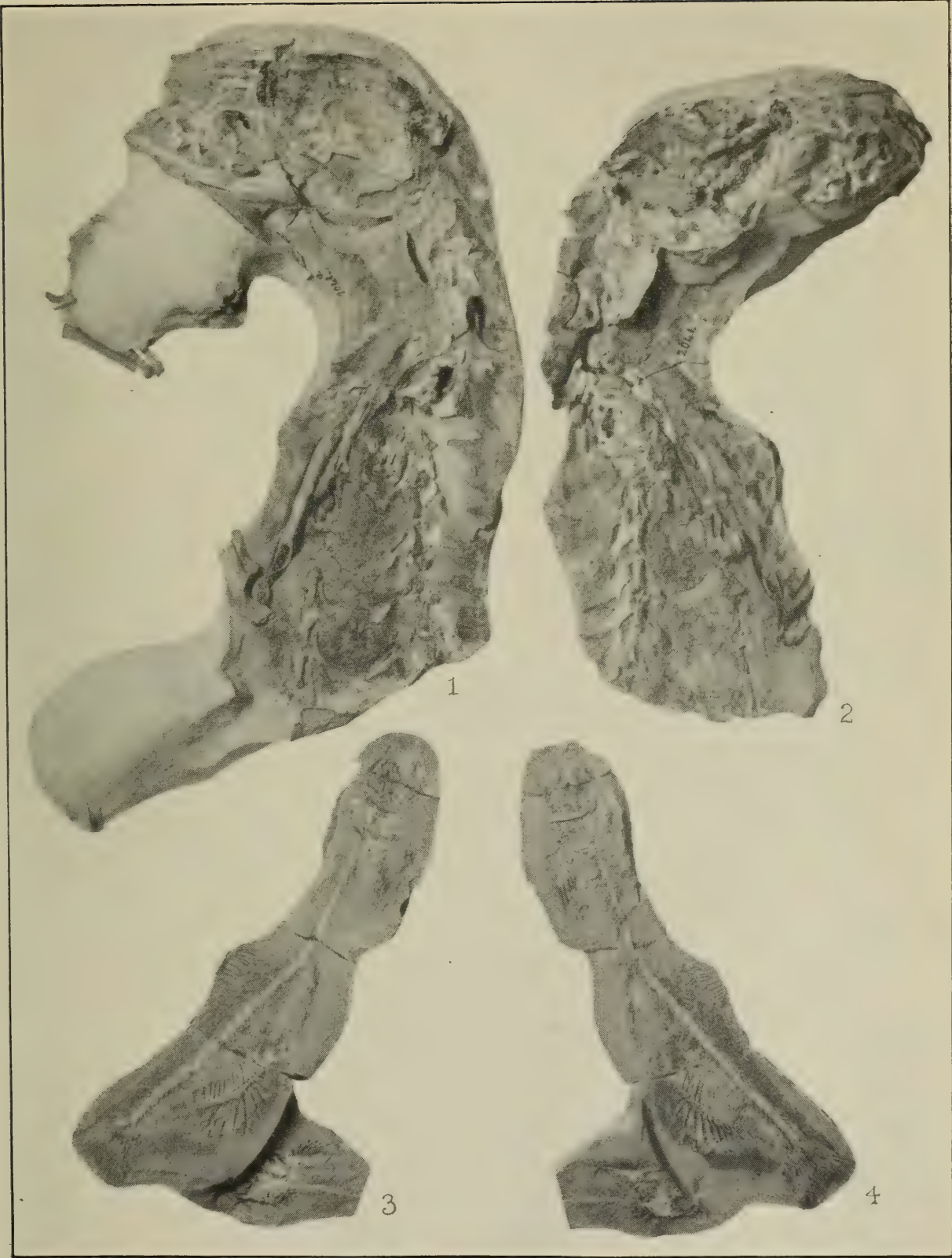
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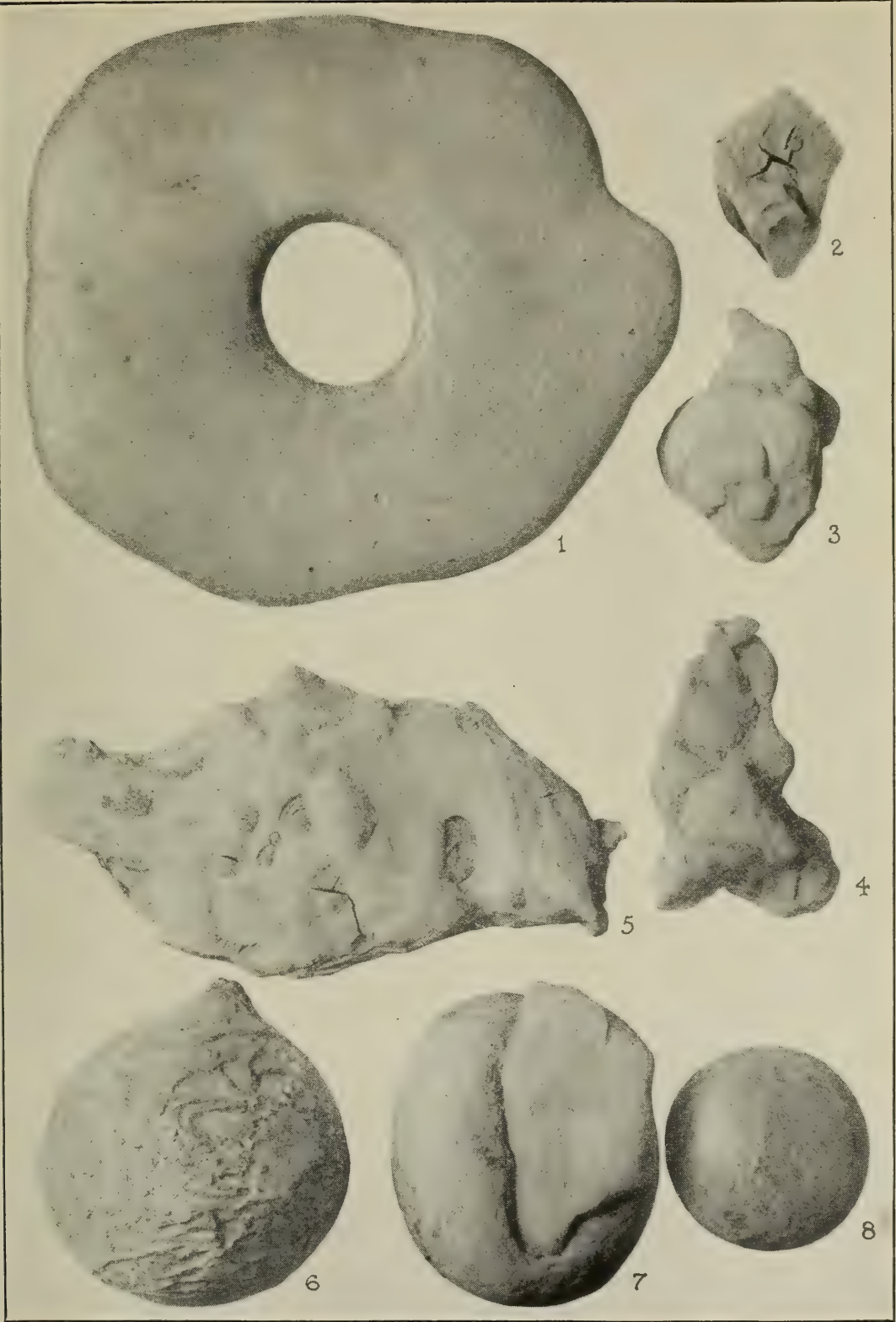
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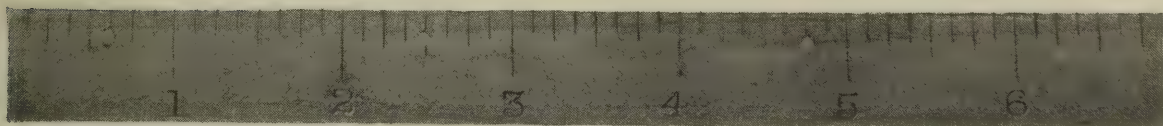
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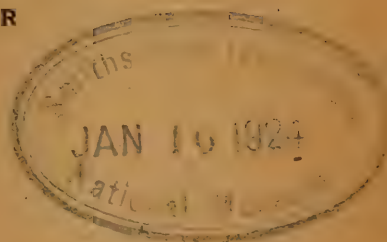
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BOUDINAGE, AN UNUSUAL STRUCTURAL PHENOMENON¹

BY TERENCE T. QUIRKE

(Presented in abstract before the Society December 29, 1922)

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PARALLEL FOLDS

Common parallel folds with horizontal axes die out upward and downward at a distance which is theoretically infinite. However, the curvature becomes almost zero at a distance about twenty times the radius of perfect curves, at the center of the structure. Thus a semicircular parallel fold 200 feet in diameter would die out at a depth of 2,000 feet. A fold of the same type, to persist for a depth of 10 miles, would require a diameter of one mile at the surface. This theoretical structure involves enormous shortening of the central line of the folds and a diminishing shortening of the flanks, until at the place where it dies out the shortening becomes zero (figure 1). Such a feature would be a remarkable case of rotational strain of a type in nature unknown to the writer.

Certain folds which die out in depth are described by Van Hise.² None of the cases cited appears to be a case of parallel folds; uniformly, the folds are in highly metamorphic rock characterized by similar folding. However, this structure is usually recognized as a probability and is commonly cited as an explanation of how folds die out at great depths.

¹ Manuscript received by the Secretary of the Society December 30, 1922.

² C. R. Van Hise: U. S. Geol. Survey, 16th Annual Report, part 1, 1896, p. 601.

This leads to the consideration of the possibility of a reversal of the position of shortening in a parallel fold.

Whereas in the type parallel fold the center is shortened and the flanks remain unchanged, would it not be possible for the center to be unshortened and for the flanks to suffer rotational shortening both upward and downward? This would lead to a parallel fold growing more and more folded on opposite sides of the central plane, the degree of curvature again being a function of the radius. In any case, the extent of the feature must depend on the persistence of the homogeneous containing

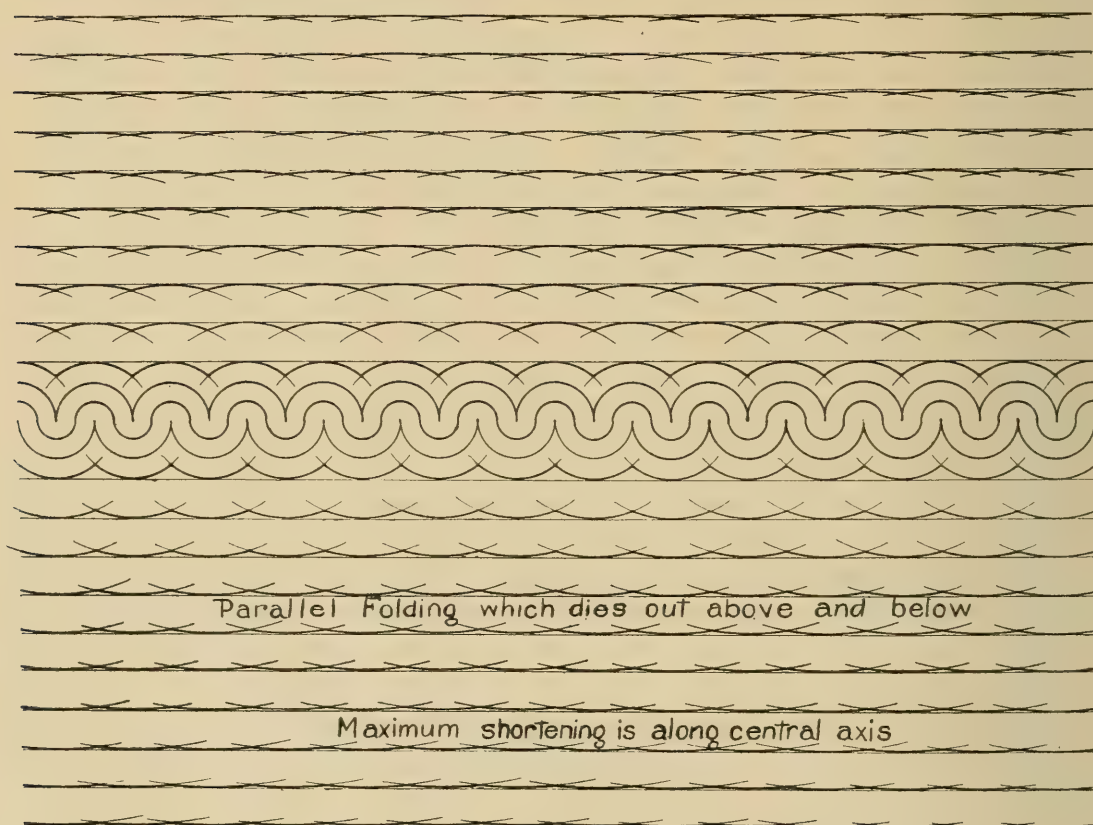


FIGURE 1.—*Theoretical Parallel Folding*

layer, without which such a feature would be impossible. Boudinage may provide such a case.

THE BOUDINS

During the early part of August, under the leading of Prof. Max Lohest, certain members of the International Geological Congress visited the region of Bastogne, in southeastern Belgium. There one has the opportunity to see, in the local quarries, a type of deformation which is so rare as to be almost unknown in any other place. This is the development of "*boudinage*," as it is called by Lohest (figures 2, 3, and 4).

The Coblencian rocks (Lower Devonian) are composed of quartzite and schist, the quartzite being in beds of from about a foot to about eight feet in thickness. The quartzite layers appear to have been compressed in the direction of their bedding, with the result that they have been thickened. The thickening has been distributed in such a way that the beds have been separated into a number of parts distinct from one another, the parts in cross-section looking like barrels, the ends of which are separated from neighboring barrels by veins of quartz.

In places where quarrying operations have removed the schists from the quartzite, one is able to see that the barrel shapes extend into cylinders which look like enormous sausages strung out side by side, from

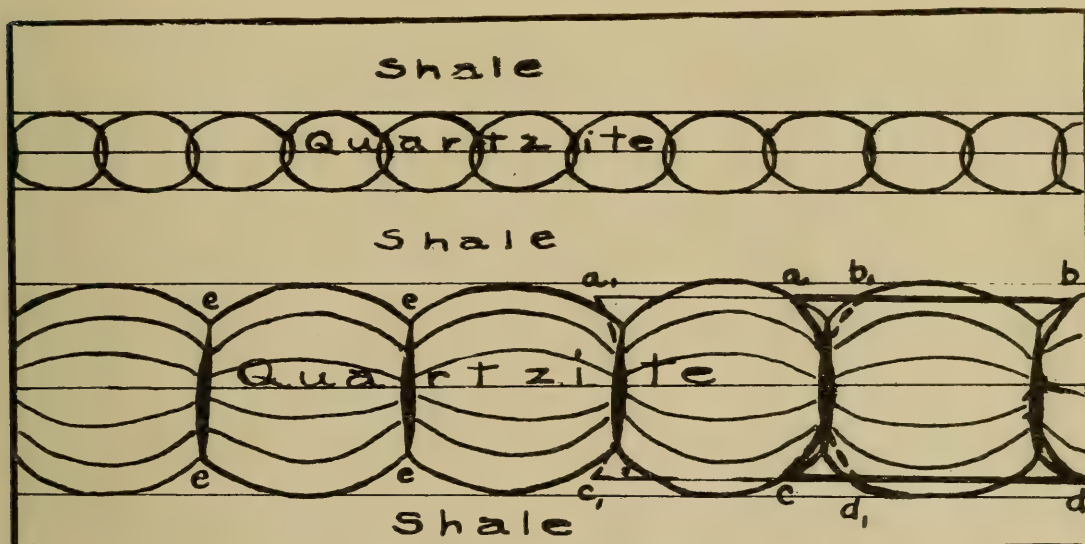


FIGURE 2.—Idealized Boudinages

The figure *a, b, c, d* shows the shape of the rock before it became a boudin. *a b* and *c d* show the maximum shortening. Shortening decreases to nothing at the axes. *e e* indicate quartz veins.

which appearance this type of deformation gets its name of boudinage. The quartz vein separating each boudin from its neighbor is quite characteristic, and the width of spacing between veins is evidently a function of the width of the bed. The boudins approximate a circle in cross-section. In small beds the circle is small; in large beds the circle is large.

THE QUARTZ VEINS

The quartz veins do not penetrate the schist above and below these bands of quartzite. They appear to be confined entirely to the beds of quartzite. It is thought by Lohest,³ following Stainier, that these veins

³ M. M. Lohest: Congrès Géologique International Livret Guide, Excursion A3, p. 8.

were formed in the quartzite previous to deformation. However, in this there is not complete agreement. Indeed, there are reasons for believing that the quartz veins were filled after the formation of the boudins.

The quartz veins in neighboring bands of quartzite are not in linear continuation. The size of veins is in relation to the thickness of the quartzite bands, being narrow in thin bands and wide in thick bands. They show no appearance of having been bent or ruptured after filling. They are typical fissure veins. The quartz veins appear to be thicker near the center of the boudins than at the edges. They seem to be lenticular, with their greatest thickness at the axis of the cylinders, according to the indication on the figures (figures 2 and 4). The quartz



FIGURE 3.—*Boudinage, Carrière de la Citadelle, Bastogne, Belgium*

veins commonly are not truly lenticular. In many cases the vein is split up into veinlets, but the total width of the veinlets along the central axis is generally greater than the width of the veins at the edge of the boudins. The position of these features in the major fold is in question, because the general structure of the Bastogne area has not yet been determined.

At the Carrière de la Citadelle the axis of boudinage appears to be horizontal, but in another quarry, at Luzery, the boudins have a dip of 35 degrees southeastward. Lohest believes that they occur only on the summits of folds, and it may be that the case at Luzery is on a roll near the summit of the anticlinorium or at the top of an anticline plunging at an angle of 35 degrees.

However, in this particular place the veins are vertical, not normal to

the dipping beds, which indicates that this is on the flank of the anticline, if we suppose the veins to follow ordinary fracture cleavage. Furthermore, in this place the veins are larger near the top than near the bottom of the boudins, and the arguments in regard to the central thickness of quartz veins do not hold.

ELASTIC AND NON-ELASTIC COMPRESSION

In general, the boudins appear to have been formed by lateral compression under enormous loading, so that the terrane has been neither arched nor crumpled, but the competent beds have been compressed longitudinally into symmetrical folds of relatively small size. During this deformation the schistose rock conformed to the more competent

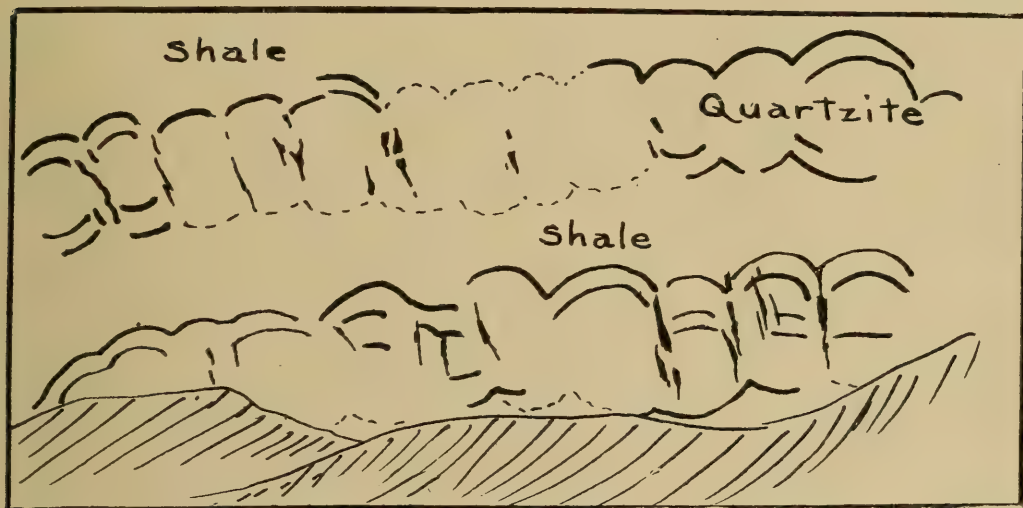


FIGURE 4.—*Boudinage, Bastogne, Belgium*

Traced from photograph used in figure 3. Transverse lines are quartz veins.

bands of quartzite, which arched both upward and downward into the less resistant phyllites. The natural conclusion is that after compression the quartzite yielded to tension, giving rise to cracks which were distributed equally throughout. The yielding to tension was more closely spaced in the thin beds than in the thick beds.

The actual openings appear to have been wider near the axes of the beds than near the edges. The edges of the boudins were folded the most. Apparently, the folded parts were straightened enough to take up the slack, but the central parts, being unshortened originally, had to supply means of expansion, and therefore cracked open instead. The central part might have been compressed during the arching of the other beds, and therefore had a certain amount of elastic recovery.

We may suppose, however, that the elastic limit of the quartzite might have been passed and the pore spaces were crushed closed. In this case the reduction might well have been as high as 7 per cent. This compression would shorten a bed three feet thick by $2\frac{1}{5}$ inches. It should be noted that this compression is non-elastic and unrecoverable on relief of pressure. A certain amount of elastic compression must accompany compression so great that the pores are closed. Recovery of this would be possible on relief of pressure.

After closing of the spaces the quartzite would have an elastic compressibility about equal to that of quartz. This is very small, being about 2.7^4 parts per million per atmosphere.

Supposing the compression to have been equal in intensity to the pressure produced by rock overburden 10 miles deep, the compression of the quartzite would have been of the order of about one-third of an inch per linear yard (0.02 per cent). Thus a quartzitic bed under great compression might be reduced $2\frac{1}{5}$ inches per yard non-elastically and one-third inch per yard elastically, resulting in a total shortening of $2\frac{8}{15}$ inches per yard. This shortening could be accommodated by the outside beds by arching.

By experiment and measurement, it has been found that a yardstick shortened by bending $2\frac{8}{15}$ inches results in an arch equivalent in height to one-seventh of its original length or to one-fifth of its reduced length. This is an arch of the shape of the outside layer of the boudins drawn in figure 5.

Supposing the boudins to have been formed by lateral forces which resulted in elastic and non-elastic compression of the axial parts and ordinary folding of the outer layers, there would have been a linear shortening of $2\frac{8}{15}$ inches per yard, of which $2\frac{1}{5}$ inches could not be recovered by expansion after relief of pressure. There would also be a thickening of the beds equal to nearly 10 inches in the widest part of the outside layers, arching upward and downward.

After relief of pressure the arches might straighten in part, but the central region has little recovery possible. If the arches lengthen again under vertical pressure or decrease of lateral support, the central part must crack open. These cracks would be greatest at the center, where arching has been zero and where non-elastic compression has been a maximum. The cracks would have a maximum width of $2\frac{1}{5}$ inches

⁴ Erskine D. Williamson: Changes of the physical properties of materials with pressure. Geophysical Laboratory, Carnegie Institute of Washington, Paper no. 446, 1922, p. 506.

per yard, or 6.11 per cent. This is about equivalent to the size of the quartz veins between the boudins.

ELASTIC RECOVERY OF FOLDED ROCKS

If we suppose, however, that the Coblencian rocks were so strong at the time of their deformation that the lateral forces were incompetent to cause the compression postulated above, we must discard the idea of change of volume of the axial material under compression. This does not eliminate, however, the possible effectiveness of the elasticity of the bent quartzite layers above and below the axial part of the boudins. On release of lateral pressure these arched layers would tend to spring back into their former shapes unless their deformation passed the elastic limit. The elastic limit of rocks is different for the tensional and for compressional strains, but the tensional elastic limit is the lower; consequently passing of the elastic limit will result in part failure of the arches by tensional cracks near the periphery. These cracks would be wide at the periphery and would decrease to zero at the axis. Veins of this type do not appear to prevail in the *Carrière de la Citadelle*, where the best observations are possible, although Lohest describes them as of that character.

Surely, some of the veins are not wider near the periphery than at the axis. Most of them appear to be widest at the axis and to pinch out to nothing, both above and below, at the periphery. This latter type appears to represent the cases of quartzite beds which were so deeply buried that under lateral compression they bent without rupture and without passing their elastic limit. On relief of lateral compression they tended to recover their former shape, thus increasing their geographical length by straightening their curves.

Lengthening of the outer beds would make openings necessary in the unfolded material within. Thus, the width of the opening is inversely proportional to the longitudinal recovery. That which was bent the most could recover the most, and that which was unbent could rebound not at all. By the elastic straightening of the bowed beds, the unbent axial beds were pulled apart. The location of these planes of rupture would naturally fall between the boudins, where the opposing spring of neighboring arches would be concentrated. Large boudins would cause wide veins; little boudins would cause narrow veins. Such is the case.

NON-ELASTIC RECOVERY OF FOLDED ROCKS

In cases where the arches passed the elastic limit another explanation is necessary. The arches were upheld against the weight of overlying

sediments by lateral compression. After decrease of this lateral support the arches tried to flatten down again. However, this can only come about by lengthening of the boudin bed. This lengthening can be accommodated easily by the arched beds, but the unbent beds must fail by jointing in the necessity of keeping up with the lateral movement of the arched layers above and below them. The result is just the same as if the beds sprang back into their former shape by elastic recovery, to wit: cross-fractures which are wide at the axis and closed at the peripheries (figures 5 and 6).

FORMATION OF BOUDINAGE

In the formation of boudinage we suppose something like the following course of events: first, the presence of very competent thin beds

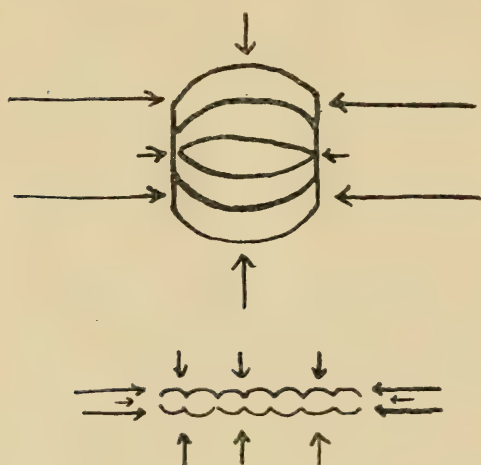


FIGURE 5.—Formation of a Boudin by lateral Pressure—a rotational Strain

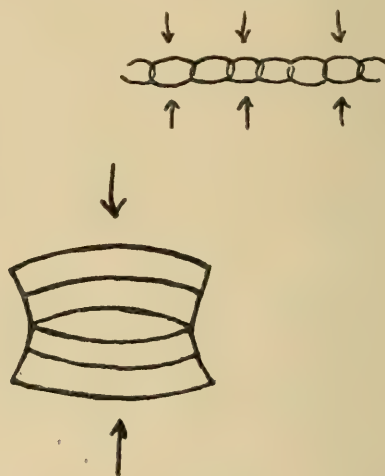


FIGURE 6.—Recovery, clastic or otherwise, of a Boudin, after Release of lateral Pressure

inclosed in incompetent material; second, the concentration on these beds of compression great enough to thicken notably the incompetent members and to telescope the competent beds into boudins. Unless the overburden were large and highly competent, the boudin member would simply arch upward. However, it arched both upward and downward to an equal degree.

PECULIARITIES OF BOUDINAGE

There are no ordinary structures or portions in ordinary folds where these boudins can be formed. They are symmetrical about a vertical axis and about a horizontal axis; therefore they can not be formed on the flanks of folds. The axis of a fold might give place to one boudin in a bed, but not to a string of them. A series of drag folds might give

rise to something like them, if cross-veins should separate them similarly. But drag folds and boudins differ essentially in their axial parts. A drag fold is folded from top to bottom; a boudin is unfolded along its axis. Drag folds affect incompetent layers between competent beds; boudins occupy competent beds between incompetent layers. Drag folds are due to shear; boudins appear to be due to extreme rotational strain symmetrical about a horizontal axial plane (figures 7 and 8).

The boudins look somewhat like the structures called phacoidal structures by the British geologists. They report the case of an epidiorite dike wrenched into a series of isolated lenticles or "phacoidal" masses imbedded in a zone of reconstructed granulitic gneiss. The case is cited

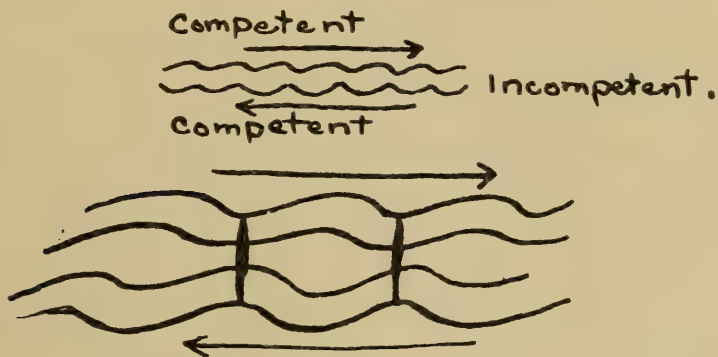


FIGURE 7.—Boudin-like Features due to Drag-folding and Cross-fractures

of a thin basic dike, disrupted and severed into seven detached lenticles of hornblende-schist, from 30 to 130 yards in length, all arranged parallel to the thrust and to the foliation planes of the reconstructed micaceous gneiss by which they are surrounded.⁵ Similarly pegmatites intruding hornblende-schists and biotite-gneisses have been broken and sheared into the same sort of forms.⁶ Very small lenticles of from 3 to 6 inches long have resulted from the thrust-plane passing above a limestone formation there brecciated for a depth of 15 inches beneath the fault-plane,⁷ and Leith⁸ cites the case of a porphyry of the Vermilion district of Minnesota which, having been sheared into rhombs, was further metamorphosed into a pseudo-conglomerate containing elongated lenses like pebbles.

All such structures are devoid of definite bedding which has any general relationship to the shape of the mass, whereas each boudin is

⁵ B. N. Beach, John Horne, and others: *Geological Structure of the Northwest Highlands of Scotland*, 1907. *Memoirs of the Geol. Survey of Great Britain*, p. 67.

⁶ *Idem*, p. 263.

⁷ *Idem*, p. 504.

⁸ C. K. Leith: *Structural Geology*, 1913, p. 66.

composed of symmetrical arches, grading from those of a high curvature at the periphery to those of no curvature along the axial plane.

Furthermore, the phacoidal structures are commonly surrounded by the enveloping layers of schistose rock wrapped about them. The boudins of a bed are side by side, unseparated except by quartz veins; never sepa-

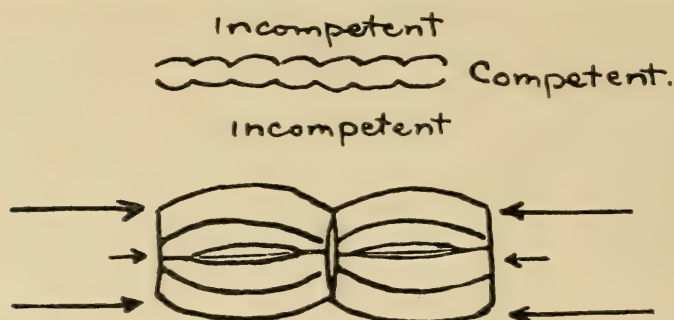


FIGURE 8.—*Boudins*

rated by the schistose rock above and below them (figure 9). We must conclude that boudins differ from all other folds and structural features.

Boudins must come as a result of some unusual type of deformation. Considering a series of boudin beds, we seem to recognize great shortening in the incompetent layers and apparently no shortening along the axes of the boudin beds. This shortening of the incompetent beds must

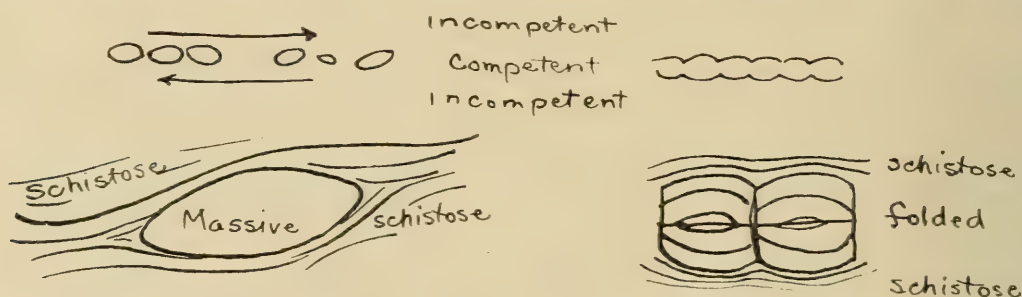


FIGURE 9.—*Phacoidal Structure (on left) and Boudins bounded by schistose Rock (on right)*

The phacoidal structure is due to rupture of competent layers and abrasion of pieces by flow of schistose matrix. The boudins bounded by schistose rock are not broken nor rounded by movement of the matrix.

result in thickening and uplift, and this uplift may approximate in shape that of a great boudin. Lohest maintains that the whole uplifted area of Bastogne is a giant boudin. If so, boudinage may offer an explanation of how some folds die out in depth, and how folds which increase in size with depth may pass out of existence at greater depth. In every case the boudins are separated from the overlying and underlying incompetent

material by shear zones. Similarly, a giant boudin may come to an end at considerable depth in contact with the deep zone of flow.

If the central part of the boudins is not compressed as much as the outer arched beds, it is difficult to understand a great stratigraphic series of boudin beds, such as Lohest postulates at Bastogne. Such a series would represent alternating shortening and non-shortening of the incompetent and competent beds respectively—an almost incredible performance.

Furthermore, a great boudin could have smaller boudins only in one row, along its central axis, which is not the case at Bastogne. And every boudin band would represent two great rotational strains swinging out from one another on opposite sides of the boudin axis, where both would be zero.

Inversely, a series of parallel folds which die out above and below represent two great rotational strains which swing in toward one another to a maximum at their union, starting from zero at distant points on opposite sides of the plane of their combination.

Although the possibility of ordinary parallel folds, so persistent that they die out according to theory, is widely recognized, the writer knows of no case where the phenomenon can be proved in the field. It is almost certain that the most promising series of parallel folds grades into similar folds at relatively shallow depth. In like manner it is probable that the Bastogne uplift will ultimately be found to be much more complicated than a simple giant boudin, although the stratigraphic series of boudin beds almost proves that the quartzitic bands were shortened by compression along their axes to a degree equal to their shortening by arching, and the boudinage is not really the structural opposite of parallel folding, but merely a very unusual type of shortening of a composite member, constituent parts of which adjust themselves to the compression by different mechanical methods. Nevertheless, the recognition of boudinage as a possible type of major folding, as well as a proved type of minor structure, may lead to happy results, and it may be helpful in explaining how deeply buried folds of large curvature may come to an end almost abruptly in contact with an incomplete zone of flow.

The boudinage of Bastogne and vicinity provides a case of a rare geological phenomenon. There is no mention of this type of deformation in any works in English, so far as the writer is aware, nor does it seem to have had consideration from any but the geologists of Belgium. There are so many geologists in America who are carrying on or planning to undertake experiments which may throw light on the cause and mechan-

ics of the deformation of the earth's crust that it is desirable that every type of structure should be made familiar to all who are interested. One of the purposes of International Congresses is to offer to the geologists of the world a convenient opportunity of visiting the peculiar or otherwise noteworthy phenomena of the country which is acting as host. Boudinage is one of those things, visited during the International Congress of 1922, which geologists may see in Belgium, although probably not known anywhere else in the world. In spite of the rarity of boudinages, they illustrate what a part of the earth's crust has done under particular circumstances and what other parts are likely to do under similar conditions, and their occurrence serves to point a warning to those undertaking mechanical experiments in structural geology. They emphasize the oft-repeated reminder that the earth's crust is not a uniform member, nor rigid, and that it is in no sense susceptible to theoretical treatment as though it were a member of uniform material and simple structure.

There seems to be nothing in the arts or in nature which can be compared in mechanical origin to boudinages, which makes them the more interesting and the more worthy of study. It is hoped that we shall learn more about them through the researches of our Belgian colleagues.

SOME CRITERIA USED IN RECOGNIZING ACTIVE FAULTS *

BY STEPHEN TABER

(Presented before the Society December 29, 1922)

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INTRODUCTION

A fault, once formed, long remains a plane of weakness, and stresses developing in the adjacent region are more likely to be relieved by adjustments along it than by the formation of new faults. This is especially true of faults that persist for long distances. The identification of active faults is of importance, since they are the loci of earthquakes, each new displacement of a growing fault resulting in an earthquake.

CRITERIA USED IN RECOGNIZING ACTIVE FAULTS

The criteria that have been used in recognizing active faults are: (1) the recurrence of earthquakes along faults, and (2) physiographic and geologic evidence of recent displacement; but each of these may be misleading unless the general stability of the entire circumjacent region be taken into consideration.

The Charleston earthquake of 1886 was one of the greatest recorded in North America, and aftershocks have continued in its epicentral area down to the present day, yet there is no physiographic or geologic evidence that crustal movements are going on more rapidly there than elsewhere in the Atlantic Coastal Plain. Therefore, disastrous earthquakes are no more to be expected in South Carolina than in other States of equal stability, such as Florida or New Jersey.

* Manuscript received by the Secretary of the Society January 14, 1923.

In regions where crustal movements are now going on with relative rapidity, as on the Pacific coast, faults showing evidence of recent displacement may be classed as active faults, and along them renewed adjustments may be expected to occur from time to time; but in regions that are relatively stable the probability of displacements in the near future is slight, even along recent faults, such as those of Mount Toby, Massachusetts.¹

Estimates of the relative stability of most regions have to be based, at present, entirely on the magnitude of post-Pleistocene movements, and on the seismic history over a period of no more than a few centuries at most. Accordingly, accurate geodetic surveys should be made in the more mobile portions of the earth, at such intervals as may be necessary, in order to determine the character and rate of the crustal movements now going on. Such surveys would probably give a better indication of the stability of a region.

PHYSIOGRAPHIC EVIDENCE OF RECENT FAULTING

Physiographic evidence is especially useful in locating active faults in regions where earthquake records are available for only a short time. Fresh fault-scarps, when present, indicate recent displacement, but scarps may be masked under thick deposits of unconsolidated sediments, and they are necessarily absent where the displacements are horizontal. Perhaps the most characteristic evidence is furnished by the presence of small depressions due to the downfaulting of narrow strips along the strike of the fault, for they seem to be equally prevalent along faults where the recent displacements have been horizontal and where they have been dominantly vertical.

The fault forming the west front of the Wasatch Range is marked by a recent scarp having a maximum height of about 100 feet, which may be traced interruptedly for a distance of about 125 miles. The facts concerning the fault given in this paper have been abstracted partly from Gilbert's monograph on Lake Bonneville² and partly from the field-notes of the present writer. In places the scarp splits up into two or more scarps, and where this branching is prominently developed narrow fault troughs and small undrained basins are prevalent. The exposed fault-planes dip toward the west at angles of 75 to 85 degrees. Striations on boulders in cemented Bonneville gravels as well as on the Carbonifer-

¹ F. B. Loomis: Postglacial faulting about Mount Toby, Massachusetts. *Bull. Geol. Soc. Am.*, vol. 32, 1921, pp. 75-80.

² G. K. Gilbert: Lake Bonneville. *U. S. Geol. Survey, Monograph I*, 1890, pp. 340-357.

ous limestone, where the two are in contact, prove that the recent displacement was chiefly vertical. The form of the scarps where they intersect narrow spurs is likewise indicative of the absence of an appreciable horizontal component parallel to the fault-plane. Variations in the height of the scarps where they cross certain post-Pleistocene features, such as alluvial fans, prove that in places, at least, the present height of the scarps is the result of more than one displacement. While no severe earthquakes seem to have occurred along the Wasatch fault since the region was settled, the evidence of relative instability in the surrounding region is such that the earthquake hazard must be rated higher than in the Mississippi Valley, which, because of the New Madrid earthquake and its aftershocks, has a less favorable seismic history.

The faulting at the time of the Owens Valley earthquake of 1872 was accompanied by the formation of numerous depressed strips. The fault-scarps have been described by Gilbert³ and Whitney,⁴ and they are well illustrated in the maps and photographs by Johnson published by Hobbs.⁵ The main scarp followed the base of the alluvial footslope of the Sierra Nevada for 40 miles, varying from 5 to 20 feet in height, and, where highest, it was paralleled by an opposite-facing, ten-foot scarp with a depressed strip between. Elsewhere the displacement was distributed over a belt of parallel, overlapping and sometimes branching faults, between which the narrow strips were depressed from 2 to 10 feet. These strips varied in width up to 200 or 300 feet, and some were several hundred yards in length. One of the depressed tracts, several thousand acres in extent, is said to have moved northward about 15 feet. Some of the fault-scarps seem to have been formed in part at a somewhat earlier period.

The San Andreas fault, extending through California for upward of 600 miles, is marked by hundreds of small depressions or sags, often holding water, and by long, narrow valleys. By means of these features the fault may be readily traced through most of its course. It is, in fact, characterized by valleys rather than by scarps. Some of the valleys are known to be diastrophic in origin, while others, such as the through valleys, are also probably due chiefly to faulting. Small trenchlike depressions were formed along the fault during the earthquake of 1906 and some of the preexisting and usually larger depressions were deepened.

³ G. K. Gilbert: A theory of the earthquakes of the Great Basin; with a practical application. *Am. Jour. Sci.*, 3d ser., vol. 27, 1884, pp. 49-53.

⁴ J. D. Whitney: The Owens Valley earthquake. *Overland Monthly*, vol. 9, 1872, pp. 130-140 and 266-278.

⁵ W. H. Hobbs: The earthquake of 1872 in the Owens Valley, California. *Beiträgen zur Geophysik*, Bd. 10, 1910, pp. 352-384.

The displacement at that time extended for over 190 miles and was chiefly horizontal, amounting to a maximum of 21 feet. Vertical displacement, where present, was small, and the low scarps faced west in some places and east in others.

Horizontal displacements along faults are scarcely mentioned in most text-books, and that along the San Andreas fault in 1906 has been regarded as exceptional; but I believe that movements of this type have been prevalent along the northern half of the fault since the Pleistocene, and that such movements have probably played a very important part in the development of the fault. The evidence bearing on this question is outlined below.

Along the northern half of the fault fresh scarps, other than those that inclose the narrow troughs, are few and inconspicuous, and yet the numerous troughs and sags furnish evidence of repeated displacements in recent time.

The fault-plane seems to be approximately vertical. It is true that the fault, instead of being a single break, is a complex of parallel and branching fractures, but the width of the zone of fracturing is seldom more than a quarter of a mile, which is small as compared with the probable depth of the fault. The fault trace formed in 1906 was not deflected where it crossed surfaces sloping in different directions. Although large vertical displacements have resulted from past movements, especially along the southern portion of the fault, there is no continuous scarp on either side; a mountain block has been uplifted in one place to form a scarp facing southwest, while in another the scarp faces northeast. Between Tomales Bay and Bolinas Bay, Lawson found evidence of large movements at different times in opposite directions, so far as the vertical component was concerned.⁶ For long distances there is no important scarp, and at a number of places the rocks exposed on both sides of the fault are the same. The fault crosses from one side of the Santa Cruz Mountains to the other, and in its long course it passes from the west side of the Coast Ranges to the east side.

Tangential thrust at right angles to the fault could not produce a vertical fault-plane nor account for the alternating scarps. It is not likely that the fault was the result of tension, for it maintains its long course, without deflection, across different kinds of rock and earlier structural features. It is not conceivable that a fault extending for such a distance with only minor deviations could originate from purely ver-

⁶ A. C. Lawson and others: The California earthquake of April 18, 1906. Report of the State Earthquake Investigation Commission, Carnegie Inst. of Washington, Publication No. 87, vol. 1, pt. 1, 1908, p. 29.

tical forces, especially since the uplift changes from side to side. If the fault was formed in none of the ways mentioned above, it must have

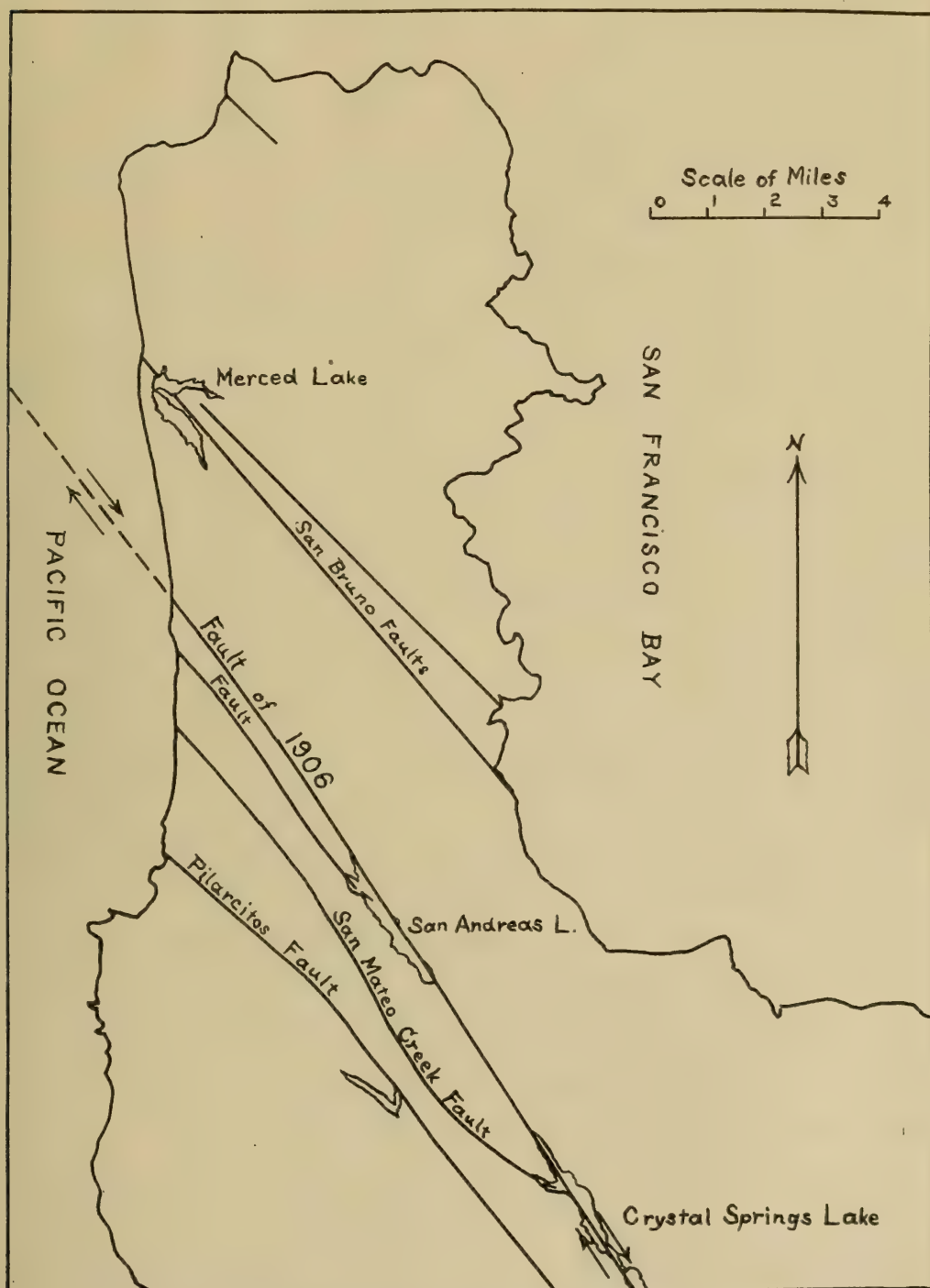


FIGURE 1.—Principal Faults on the San Francisco Peninsula

After A. C. Lawson, with additions by Stephen Taber

originated through shearing in a horizontal direction; and, once formed, local stresses due to uplift of adjacent areas would be relieved by vertical adjustments along it.

The branch faults that leave the main San Andreas fault on the San Francisco Peninsula, such as the Black Mountain fault, the San Mateo Creek fault, and a fault located by the writer, which extends from the western branch of San Andreas Lake and reaches the coast a half mile south of Mussel Rock (see figure 1), are all readily explained on the hypothesis of horizontal shear. Branch faults of this type are not a characteristic of normal faulting or of reverse faulting. The numerous small ponds between Mussel Rock and San Andreas Lake indicate that there are several other branch faults in that section.

Several displacements are known to have occurred along the San Andreas fault since the settlement of California, though in most instances the direction of movement is unknown. Vertical displacements, however, are much more likely to be recognized and reported than horizontal ones, especially in thinly settled regions, and the scarps formed are conspicuous for years. In 1857 the southern half of the fault was ruptured, but the direction of displacement was not recorded. In 1890 a rupture is said to have occurred near San Juan, with a small displacement in the same direction as in 1906. During the earthquake of 1901 a crack was formed along the fault in the Cholame Valley which could be traced for several miles.⁷

The earthquake of January 31, 1922, which originated under the Pacific Ocean about 300 miles off the Oregon coast and approximately in line with the San Andreas fault, was felt much farther from the origin than the earthquake of 1906. It likewise was probably caused by a horizontal displacement along the San Andreas or some parallel fault; for, as there was no sea wave, there could have been no appreciable vertical movement of the sea-floor.

While it is outside the scope of the present paper, I wish to point out that the forces necessary to produce the displacements now in progress along the San Andreas fault must be regional and not local, and that there are other faults parallel to the San Andreas fault, such as the Haywards fault, on the opposite side of San Francisco Bay, which show the same physiographic characteristics.

ORIGIN OF SMALL FAULT TROUGHS ALONG ACTIVE FAULTS

Several hypotheses have been advanced to explain the formation of the small fault troughs and depressions formed during earthquakes. Fuller suggests that those formed at the time of the New Madrid earthquake were due to undermining caused by the creep of quicksand into

⁷ A. C. Lawson and others: *Op. cit.*, pp. 38 and 40.

ivers.⁸ This might account for circular and more or less irregular-shaped depressions, but hardly for rectilinear trenches with such sharp steep sides and flat bottoms that they suggest canal excavations. The hypothesis is certainly inapplicable to the depressions mentioned in the present paper.

Gilbert, in explaining troughs at the base of the Wasatch scarp, assumed that the fault-plane separating the alluvium from the firm rock of the mountain had a dip of 60 degrees, and that the recent uplift of the mountain block relative to the alluvium resulted in a break which, as it approached the surface, curved upward away from the fault-plane so as to leave a triangular prism of alluvium attached to the rock constituting the footwall. The open fissure formed by faulting along the up-curving surface would be immediately filled by the settling of one or both walls.⁹

The objections to this hypothesis are: (1) that depressions are absent for long distances where there is a single fault-scarp instead of several branching fractures and there is no other evidence of open fissures having been formed; (2) that pressure effects, such as striations, are found along the fault surface in gravel cemented by calcite as well as on the solid rock; (3) that at the only place where the fault-plane was observed in solid rock the dip was as steep or steeper than in the alluvium and glacial drift; and (4) that it is not applicable to similar troughs along the San Andreas fault where the displacement was horizontal, or to those formed in solid rock during the earthquake at Yakutat Bay, Alaska.¹⁰

Later, Gilbert explained the sags and ridges along the San Andreas fault in the Bolinas-Tomales Valley as due to "the unequal settling of small crust blocks along a magnified shear zone,"¹¹ but he advanced no theory to explain the settling. The horizontal displacement of 1906 was accompanied in places by slickensides and similar evidence indicative of compression normal to the fault rather than of tension.

Oldham attributed the formation of certain depressions during the Assam earthquake of 1897 to the lurching of alluvium at the base of hill slopes, but such depressions follow the windings of the contact between hill and plain.¹²

⁸ M. L. Fuller: The New Madrid earthquake. U. S. Geol. Survey, Bull. 494, 1912, pp. 48-58.

⁹ G. K. Gilbert: Lake Bonneville. U. S. Geol. Survey, Monograph I, 1890, pp. 355-356.

¹⁰ R. S. Tarr and L. Martin: The earthquakes at Yakutat Bay, Alaska, in September, 1899. U. S. Geol. Survey, Prof. Paper 69, 1912, p. 37, and plate XVII, C.

¹¹ G. K. Gilbert: "Characteristics of the rift" in the California earthquake of April 18, 1906, vol. i, pt. 1, 1908, pp. 33-34.

¹² R. D. Oldham: Report on the great earthquake of 12th June, 1897. Mem. Geol. Survey India, vol. 29, 1899, pp. 92-93.

Troughlike depressions and undrained basins may be formed on sloping surfaces by a warping or selective uplift of the lower side of a fault, but in most cases the uplift is on the opposite side and therefore tends to accentuate the slope.

A careful study of the small fault troughs and other depressions found along several active faults has led the writer to the conclusion that most of them are due to the downthrow of narrow blocks or wedges within a belt of parallel and interlacing fractures. The settling of the blocks is believed to take place while the rocks are momentarily separated by the passage of earthquake vibrations. The formation of these small troughs and sags is, therefore, regarded as a result of earthquakes and not as a cause, though it is probable that some aftershocks are due to minor displacements of blocks which have not reached a position of complete stability during the earthquakes.

During the California earthquake of 1906 a fault fissure was opened so wide as to admit a cow, which fell in head first and was thus entombed, the closure leaving only the tail visible. At this point a trench was formed 6 to 8 feet wide and 1 or 2 feet in depth.¹³

When a small fault trough is formed in rock that is buried under thick deposits of unconsolidated sediments, the surface manifestations may be no more than a shallow depression without definite boundaries. It was largely by means of such depressions that the writer traced the Inglewood fault of southern California.¹⁴

Ridges are sometimes left between two downfaulted blocks, but most of the low ridges formed during the California earthquake of 1906 were due to the breaking up of surface soil into a loose aggregate of irregular clods or blocks, with a consequent high percentage of voids, and they gradually disappeared as the material again became compacted.

The hypothesis advocated above is not applicable to large fault troughs having a width of several miles, which seem to be formed as a result of repeated displacements, sometimes on one side and sometimes on the other. The displacements which result in the formation and growth of large fault troughs are, therefore, regarded as a cause of earthquakes and not as effects.

¹³ G. K. Gilbert: "The earth movement on the fault of April 18, 1906—Tomales Bay to Bolinas Lagoon," in the California earthquake of April 18, 1906, vol. 1, pt. 1, 1908, p. 72.

¹⁴ Stephen Taber: The Inglewood earthquake in southern California, June 21, 1920. Bull. Seis. Soc. Amer., vol. 10, 1920, pp. 139-142.

THE LAKE SUPERIOR GEOSYNCLINE ¹.

BY W. O. HOTCHKISS

(Presented before the Society of Economic Geologists Dec. 29, 1922)

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INTRODUCTION

The rocks surrounding the western half of Lake Superior dip to the southeast in Minnesota and northern Douglas County, Wisconsin, and dip more steeply northwestward in the limb extending southwestward from Keweenaw Point to Minnesota. As the main axis is not far northwest of the outcrop of the south limb, the syncline is not symmetrical. Dips of 25 to 30 degrees are unusually high on the north limb; on the south limb dips vary from 30 to 90 degrees.

The purpose of this paper is to discuss briefly the major facts as they are now revealed to us in the rocks of this syncline and to construct a hypothesis correlating these major facts in its history. This hypothesis relates the origin of the various formations and their present structure to the intrusion of an enormous bathylith, whose final result is evident to us in the scores of thousands of cubic miles of Keweenawan lavas and intrusives. The gradual foundering of the roof of this bathylith is believed to offer the most plausible explanation of the origin of the present structure.

¹ Manuscript received by the Secretary of the Society April 19, 1923.

FORMATIONS INCLUDED IN THIS SYNCLINE

The oldest rocks in this syncline are the Keewatin greenstones and Laurentian granites. These had undergone much deformation and metamorphism and were base-levelled before Huronian time.

On this plain were deposited the Huronian sediments of the Mesabi and Gogebic districts. The rocks of these two districts are so much alike that only those in the Gogebic are described. On the Archean basement is first a Lower Huronian dolomite, present in the Gogebic but lacking in the Mesabi. Remnants only are left of this. Next follows the Palms quartz slate, which has a fairly uniform thickness of 500 feet over most of the range, but thickens rapidly at the east end to about 1,000 feet. This is a greenish gray, unoxidized formation.

The Palms is succeeded by the Ironwood formation. This is about 500 feet thick at the west and thickens gradually to about 1,150 feet at the east end of the range. The same beds which make up the 500-foot section on the west are 900 feet thick in the east. The top of this formation has certainly been eroded, but the differences in thickness are probably due more to original deposition than to erosion.

The Ironwood is succeeded by the Tyler formation—a great unoxidized, greenish gray slate and graywacke series with much iron carbonate near the base. It reaches a thickness of $2\frac{1}{4}$ miles a short distance west of the Michigan-Wisconsin line and tapers to nothing 20 miles to the east and west. Here again the top of the formation is eroded, but how much the varying thickness is due to erosion and how much to original deposition can not be stated with certainty. Again both factors probably enter into the complete story.

The Tyler is followed by the Lower Keweenawan sandstone or quartzite and conglomerate. This formation is poorly exposed and probably is not always present. Its thickness is less than 100 feet, as a rule. It is chiefly a brown to yellowish oxidized formation. When pebbles are present, they are predominantly of quartz porphyry.

Then follow the Middle Keweenawan basic flows and intrusives, with occasional quartz porphyry flows and intrusives, and acid conglomerate and quartz sand beds. This series varies in thickness from 3 miles to 6 miles.

DIRECTIONS OF SLOPES ON WHICH SEDIMENTS AND FLOWS WERE DEPOSITED

The direction of the original slope of the Archean baselevel is not known.

The Palms quartz slate is a shallow-water deposit with ripple-marks nearly parallel to the present strike, but pitching down to the east a few degrees. These ripples have been interpreted as possibly being parallel to the shore. Which way this shore lay—to the north or south—is not indicated. Its uniform thickness over most of its area and rapid thickening at the east indicates a bottom that was level and sinking at a uniform rate except at the east end, where the sinking was more rapid.

The Ironwood formation, by its parallelism to the Palms, indicates a continuation of Palms conditions as to slope of bottom, with probably a more general tilting to the east indicated by the gradual thickening of the formation in that direction.

The Tyler slate (and graywacke) was preceded by some erosion, but wherever observable its lower beds are essentially parallel to the Ironwood. Its character indicates a gradual sinking of the bottom and a fairly rapid accumulation of the sediment in relatively shallow water. Whether its thick middle and thin ends are due to more rapid sinking of the middle and consequent thicker deposition or to deposition of a uniform thickness and later erosion is not known, but it is probably due to both. At any rate, the general axis of the basin must have been nearly parallel to the present outcrop. The shore may have been either to the north or south so far as evidence from the formation is known.

The Lower Keweenawan sediments have not been studied sufficiently to be sure from which direction they came. Such evidence as we have is slight and conflicting in character. The flows give much better evidence with few conflicting features. In a quarry in the base of the flows north of Ironwood the second flow advanced over a thin mud deposit and squeezed it up before it in such a manner as to indicate that the flow advanced from a northerly direction.

A second line of evidence is the fanning of the dips. The flows at the south are much steeper than those at the north in practically every known section. This can be explained as the normal decrease in dip of the beds toward the middle of a normal compression syncline. It can equally well be taken as an indication of flows thickening away from the source to fill a sinking syncline, but this implies a source outside the syncline for which good evidence is lacking. It is believed that the flows thinned away from the source in normal fashion and that this thinning up the present dip indicates a source now concealed down the dip.

A third line of evidence for the direction of movement of the flows was seen with Graton and Butler and their associates this past summer in the Calumet and Hecla mine. Here the bottom of the flow that covered the Calumet and Hecla conglomerate showed a great number of

long-drawn-out "pipe" amygdules nearly perpendicular to the base of the flow. These were believed to be due to steam produced by water present in the conglomerate. The tops of these pipe amygdules were uniformly bent up the dip, indicating that just before solidifying the lava was moving upward in relation to the present dip, or, in other words, that the slope on which it flowed was down to the south and east. One case of cross-bedded sand in the base of the conglomerate was called to my attention by Doctor Lane. This showed that the depositing water current at that point was flowing in the same general direction—downward to the southeast.

Though it may not be held that the evidence is conclusive that the original Keweenaw slopes in the Gogebic district were all downward to the south and east, nevertheless what evidence is available is practically all in agreement with this conclusion and justifies as a working hypothesis the assumption that the source of the flows was in the present bottom of the syncline. Further evidence is needed, and, whatever its character, will doubtless be forthcoming in future geologic work on these formations.

EVIDENCES OF TILTING OF THE LAND SURFACES

A cross-section from the Archean baselevel to the Upper Keweenaw sandstones through Bessemer was made by Gordon for the Michigan Geological Survey and published in 1906. This is typical for the whole range and shows the Ironwood dipping north 60 degrees, the lowest Keweenaw flow dipping north about 80 degrees, and a gradual lowering of the dip to 30 degrees in the outermost flows.

If we accept as a working hypothesis that the flows were poured out on a south-sloping surface from a source to the north of the present outcrop, then the iron formation must have been tilted at the time of the first flow so that it had a southward dip of 20 to 30 degrees. This indicates a rising of the land to the north, which had apparently been progressing all through the deposition of the Tyler, as we find the northern outcrops of that formation often dipping more steeply than the iron formation and the basal beds of the Tyler.

If the source of the flows continued to be the same—north of the present outcrop—then the greater elevation of the surface to the north must have been maintained continuously throughout the accumulation of the flow series. The surface of each succeeding flow must then have marked a gentle southward slope at the time of its outpouring. This being the case, the decrease in present dip of the upper flows as compared to the lower must indicate a gradual tilting of the lower flows and the Huronian

beds as the flow series was accumulated. The Huronian iron formation, which dipped south 20 to 30 degrees at the time of the first flow, was, if the above interpretation is correct, gradually tilted back so that it had a horizontal position when the flow series had attained a thickness of about 2 miles, for flows that far up in the series are parallel to the iron formation. The tilting continued so that when the uppermost flow was extruded on the south-sloping surface the lowermost flow dipped about 50 degrees to the north. The tilting continued during the deposition of the Upper Keweenawan sandstones.

OTHER FACTS TO BE FITTED INTO THE STORY

Numerous dikes cut the Huronian and some of the lower Keweenawan flows. They evidently filled major joints in the main, for they have a general parallelism. In general, they pitch downward to the east about 15 degrees from the horizontal and dip about 45 degrees to the south. Thus their strike at the surface is now northeast where the iron formation strikes east.

In the lower part of the iron formation is a great bed fault which displaces the dikes and the younger part of the formation upward and eastward 800 to 900 feet in the westernmost mines and 500 feet in the region of Bessemer.

A great gabbro laccolith extends from the Wisconsin-Michigan line westward for 50 miles. It maintains a thickness of 2 miles in its western part, and west of Mineral Lake bulges to a thickness of 4 miles. Field work in 1923 indicates that this is not a single laccolite, but rather a series of parallel laccolitic intrusions into the lower part of the flow series.

Another fact to fit into the story is the great abundance of acid sediments interspersed between the flows. According to Lane, in the Bessemer section the amount of these is much greater than the total mass of acid igneous rocks now visible, and also much greater in amount than the basic sediments. Acid conglomerates exist in Wisconsin directly associated with acid flows, and it is believed that the sediments represent partial erosion of such flows, which, however, did not get so far from the volcanic source as the sediments.

HYPOTHESIS EXPLAINING THE FOREGOING FACTS

GENERAL STATEMENT

The origin and structure of the rocks of the Lake Superior syncline fit in with the story of a great bathylith. It is my conception that this

bathylith rose from great depths within the earth slowly and through long geologic periods; that it was rising during all Huronian time, and played an important part in determining the character and thickness of the Huronian deposits. This hypothesis is advanced to be criticized, to see whether it is possible to relate all the major facts as suggested in this paper or whether there are insuperable difficulties that may be brought forward.

SIZE AND SHAPE OF THE BATHYLITH

The size of the bathylith is indicated in part by the amount of material extruded. The main part of the trap-rock syncline—from near Minneapolis to the end of Keweenaw Point—is 300 miles long. It averages about 80 miles in width. If the hypothesis here advanced is correct, the average thickness of igneous rock would be well over 4 miles. This indicates a total volume of the order of magnitude of 100,000 cubic miles—enough to cover the New England States and the State of New York with lava flows a mile in thickness. How much of the original magma solidified within the chamber in addition to that extruded we have no means of knowing. While this amount was probably large, it can be neglected in our present consideration. Assuming that the bathylith was elongated parallel to the axis of the present syncline and equal to it in length, we have a cross-sectional area of at least 320 square miles (4×80). While it is probable that the shape of the bathylith in cross-section varied greatly from time to time during its rise from the position of origin, it seems most probable that its vertical diameter was much greater than the horizontal. If the horizontal diameter was 8 miles, the vertical averaged 40 miles. Any pair of diameters can be selected to meet the reader's ideas of what is most probable mechanically.

RISE OF THE BATHYLITH AND ITS CONSEQUENCES

The rise of the molten mass in the deeper portion of its travel must have been approximately like that of a drop of oil rising in water—the material above it flowing very slowly to the sides and that adjacent to the lower part flowing in—a gravitative phenomenon, the molten mass rising because it was lighter than the surrounding rocks. If the molten rock were 2 per cent lighter than the surrounding solid rock (assuming a specific gravity of 3.00), the differential pressure on the top of the magma reservoir would be about 130 pounds per square inch for each mile of vertical diameter of the fluid mass. There would be a minimum vertical diameter of the fluid mass determined by the force with which the overlying solid rocks resisted being pushed aside. If the vertical

dimension of the magma were too small, sufficient differential pressure would not be developed to force the superjacent rocks aside. As this dimension increased, the rate of rise would be more rapid. We know too little of the effect of differential pressure on rocks subjected to the temperature and pressure at great depths to know what pressure would be necessary to cause a magma to rise, so the best idea we can express is that the horizontal dimension of the fluid mass was probably much less than the vertical.

With this necessarily somewhat vague picture in mind—of the size and shape of the rising magma—let us start with the Archean baselevel, take up the various events in order, and point out how each might be, and possibly is, related to the great intruding mass.

One of the early surface manifestations of the rise of such an extremely large mass of magma would be the elevation of the surface, the magma floating the surface rocks up. This might well occur long before any other surface evidence of a molten mass below. Assuming the position of the magma to be under the axis of the present syncline, a gentle doming of the Archean baselevel would take place, with resultant slopes down to the northwest and southeast, the long axis of the elevation being parallel to the present synclinal axis. This elevation would revive erosive processes and sediments would be deposited in the water-filled depressions on the flanks of the dome. These depressions can well be imagined to be produced by the “undertow” of rock flowage—away at the top, down at the sides, and inward toward the bottom of the magma. These first sediments form the Huronian formations, chiefly the quartz slates, underlying the iron formation in the Mesabi and Gogebic iron districts. The inference from Palms ripple-marks that the shoreline extended in a northeastern direction fits with the tilting ascribed to the magma.

The next major event is the deposition of the Mesabi and Gogebic iron formations. Van Hise and Leith, in Monograph LII of the United States Geological Survey, ascribe the origin of these formations to magmatic water which contributed the iron and silica in solution to the water bodies in which the formations were deposited. In my own study of the Gogebic such a source seems to be the only one that offers an adequate explanation. These silica-iron-bearing waters may be considered to be the first surface contribution of the great mass of magma we are considering—a pre-volcanic emanation of vast volumes of solution that gave the first surface relief from pressure below. This relief might well result in a pause in the elevation of the surface and a more or less

complete cessation of clastic deposition while the nearly pure chert and iron oxide formation was being deposited.

As the effect of this relief disappeared the eroded Archean rocks of the dome would again rise and a renewal of clastic deposition to the north and south of the dome would follow. These deposits are the Virginia and Tyler formations of the Mesabi and Gogebic districts. Progressive elevation of the dome and sinking of the trough during this deposition explains the changing dip angles of the Huronian beds which we find in the Gogebic district in going from the base to the top. At the close of this period the basal beds of the Huronian dipped 20 to 25 degrees south and the top was level.

The next major event was elevation of the surface, probably more rapidly than at any previous time. The top of the Huronian rocks in the Gogebic district was eroded and the eroded surface more or less completely covered with a new type of deposit—a thin land deposit of quartz feldspar sand with pebbles of quartz porphyry, an oxidized yellow or red formation, very different from the green, unoxidized sediments beneath. This was quickly followed by a rapid outpouring of basic lavas.

These last events are readily explainable by assuming that the magma was nearing the surface and about ready to break through. The rapid elevation and erosion at the close of Huronian deposition fits perfectly with this assumption. The source of the quartz-feldspar sands and porphyry pebbles can be found in the first extrusions of lava, which may well have been acid. Being more viscous, these would not flow far to the south and so might not be expected to be in evidence along the present outcrop. Later outpouring of the more fluid basic material would cover the Lower Keweenawan quartz-feldspar sands and porphyry conglomerate.

Lane and Gordon² have estimated that the acid eruptives evident in the Black River section are about one-thirtieth as great in mass as the basic eruptives. On the other hand, the acid sediments derived from acid eruptives are about sixteen times as great in mass as the basic sediments and about four times as great as the acid eruptives. This must indicate that close to the vents there were much greater volumes of acid eruptives than are exposed at the greater distances where the series is cut by the present surface. This is in accord with the common observation that acid lavas are less fluid and tend to pile up relatively near the source.

After the surface outpouring of lava began there were undoubtedly

² Michigan Geol. Surv., Ann. Rept. 1906, p. 420.

alternating periods of slow and rapid extrusion. Some portions of the main volcanic range would be quiescent while others were active. In any given part of the range there would be periods of activity and periods of quiescence. During the quiescent periods the magma beneath would have time for partial differentiation. At the surface erosive agents would find time to spread acid conglomerate and sandstone beds over the flanks of the range, the material for which they found in the acid flows in the higher areas. When extrusion began afresh, the character of the flows would differ, more or less, from the preceding flows to correspond with the degree of differentiation that had taken place. This variation in character is strikingly brought out in Mr. Aldrich's magnetic work in northern Wisconsin this past summer.

During the time of the extrusion there was a slow progressive sinking of the range which nearly kept pace with the thickness of the extruded flows. This sinking was probably one of the chief causes of the continuance of extrusion—the load sank into the magma reservoir and squeezed the magma out. This sinking affected the area for many miles on either side of the vents and included the Huronian rocks and the Archean rocks to the north and south. The ancient Archean baselevel in the Gogebic district was thus tilted back to a horizontal position, then northward, so its present dip is about 60 degrees to the north.

After a moderate thickness of the lower basic flows had been extruded, numerous dikes found their way along tension cracks into the strike joints of the Huronian. At a later date these dikes were sheared by a great fault, an eastward and upward thrust of the upper part of the series parallel to the beds. Lane³ has suggested that this may be correlated with the intrusion of the gabbro laccolith in Wisconsin. This intrusion may also be contemporaneous with the development of the great Keweenaw thrust-fault, and the two upward thrusts of the north part of the series on the Gogebic may be a part of the same general readjustment. This could be accounted for mechanically as a gradual differential sinking of the outer rocks into the magma reservoir to force more lava out of the vents. These fault adjustments probably began when the northward dip of the lower flows was less steep than at present.

At the time of the final extrusion there was most probably a high central range largely composed of acid flows. From this range was derived a goodly part of the Upper Keweenawan conglomerates, sandstones, and shales which have been estimated by Thwaites⁴ to have a maximum thickness of nearly 25,000 feet.

³ Loc. cit., p. 470.

⁴ Wisconsin Geol. and Nat. Hist. Surv., Bull. xxv.

During the deposition of these sediments there was probably progressive sinking due to the cooling and contracting of that part of the original magma that was not extruded. The cooling and solidifying of this mass would result in giving off large quantities of solutions and gases, and the contraction would result in settlement and readjustment of the lava flows above it to make channels for the escape of the solutions. It is suggested that this igneous after-effect may be appealed to as the source of the copper mineralization which the members of the geological department of the Calumet and Hecla Mining Company have presented to us.

After the deposition of the Upper Keweenawan sediments orogenic pressure from the southeast resulted in tilting the sediments and increasing the northward dip of the south limb of the syncline. This stress resulted in a great thrust-fault across northern Douglas County, in Wisconsin, which throws the middle or lower part of the flow series in contact with the youngest Upper Keweenawan sediments known.

The succeeding history of the Lake Superior syncline has been one of gentle elevations and sinkings in all following geologic periods, in which the structure has not been altered, but has acted as a unit. The only modification has been that due to erosion, which has developed the surface as we see it today.

PRE-CAMBRIAN FOLDING IN NORTH AMERICA ¹

BY WILLIAM J. MILLER

(Presented before the Society December 29, 1922)

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INTRODUCTION

Any serious attempt to decipher the pre-Cambrian paleogeography of the continents, even if only in broad outline, should be commended. An

¹ Manuscript received by the Secretary of the Society February 26, 1923.

elaborate effort of this kind has very recently been made² by R. Ruedemann, whose paper is valuable mainly because of its highly suggestive features. In it he "ventures to suggest some possible fundamentals of pre-Cambrian paleogeography." It is not too much to say that Ruedemann has opened up a new and important field of geological inquiry.

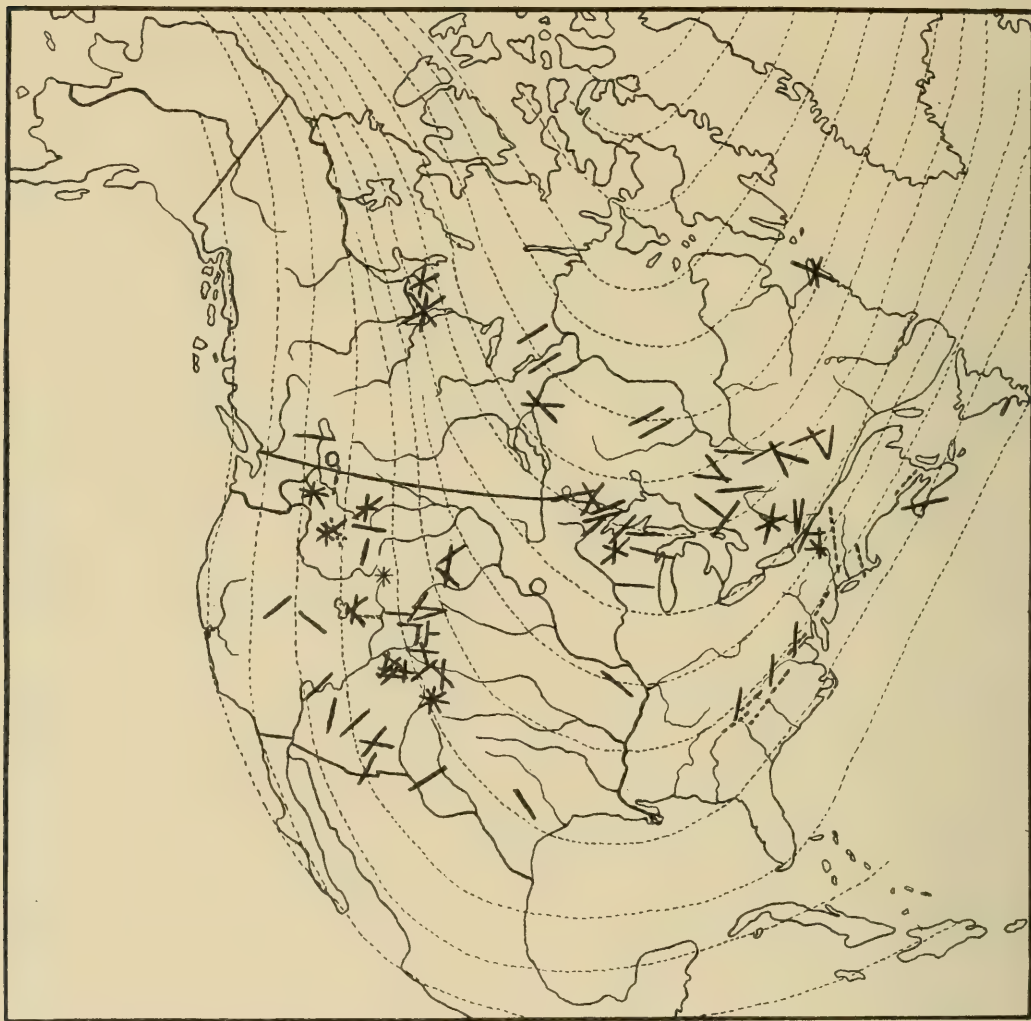


FIGURE 1.—*Map of North America*

Showing, by the short, heavy lines, observed strikes of pre-Cambrian folding and foliation and, by the long, curved, dotted lines, the pre-Cambrian structural trend-lines advocated by Ruedemann. The short, broken lines indicate strikes of pre-Cambrian rocks developed mainly or wholly in post-Cambrian time.

The present purpose is to confine attention to one very important aspect of the subject, in which the writer has been interested for some years, and this in its application to North America only. This aspect of the subject is the folding and foliation of pre-Cambrian age, with special

² R. Ruedemann: N. Y. State Museum Bulletin 240, 1922, pp. 67-152.

reference to their trend-lines. This is a fundamental consideration in Ruedemann's paper, and in his summary regarding the principal lines of pre-Cambrian folding in North America he says:

"The northeast of North America, including Greenland, exhibits a distinct northeast direction. . . . This northeast direction swings in the interior of the continent into an east-west line, and the latter turns into a north-south line as it approaches the Rocky Mountain region. The pre-Cambrian folding of North America exhibits thus a grand and simple curvature (see accompanying map), which clearly proves this part of the earth to have acted as one unit against the diastrophic forces active in pre-Cambrian time."

Ruedemann's conclusions regarding the trend of pre-Cambrian folds and foliation should not go unchallenged; for, as a glance at the accompanying map shows, most of the actually observed strikes of pre-Cambrian folds and foliation fall far short of warranting the representation of these structures in the form of "a grand and simple curvature."

Before proceeding to a discussion of observed strikes of pre-Cambrian structures, attention should be directed to certain important general considerations which must be constantly kept in mind in any attempt to deal with pre-Cambrian diastrophism.

GENERAL CONSIDERATIONS

DEGREE OF FOLDING OF EARLIER PRE-CAMBRIAN ROCKS

Most writers on the subject seem to take it for granted that the earlier pre-Cambrian rocks are everywhere severely folded and highly metamorphosed. Ruedemann, for example, states (page 75) "that the Archean basement complex has undergone not only complete metamorphism, but also a worldwide intense folding." The present writer believes that the facts for certain (or possibly many) regions are opposed to such a sweeping assertion. He published a rather elaborate paper³ in 1916 in which, after critically examining the field facts and the views generally held, he concluded that the whole Adirondack area of earlier pre-Cambrian rocks, excepting the extreme northwestern side, has never been subjected to anything like severe orogenic pressure, and that the influence of the large-scale magmatic intrusives, accompanied by not more than very moderate lateral pressure, more satisfactorily explains the rock structures. The Adirondack Grenville (Archean) sedimentary series generally has its stratification remarkably preserved, and many large areas of the rock are either in nearly horizontal position or show only moderate tilting. Ruedemann states that these rocks have

³ W. J. Miller: Jour. Geol., vol. 24, 1916, pp. 587-612.

been highly compressed, and he mentions (page 76) a number of writers on the geology of northern New York in support of his contention. He might have added that a dozen years ago the present writer held the same view; but several of the writers mentioned have never professed to have seriously studied this problem, and several others give evidence only for the northwestern (Saint Lawrence Valley) side of the Adirondack region, which the present writer also believes does show evidence of more or less folding. For the ten thousand square miles of the Adirondack region proper, however, only two men, Cushing and Alling, have really argued for severe, even isoclinal folding, and they have largely ignored the array of evidence to the contrary, as set forth by the present writer in the paper above cited. Unless this array of evidence is seriously taken up and disproved, it is hardly fair to merely state without proof, as Ruedemann does, that the conclusion from that evidence is wrong. Ruedemann gives considerable attention to the pre-Cambrian of northern New York because it is a distinct, unusually studied area, in many ways "representative of the whole problem" of pre-Cambrian folding.

Another area of earlier pre-Cambrian rocks which has been carefully studied is the Haliburton-Bancroft district,⁴ covering over four thousand square miles of eastern Ontario, Canada. The region consists mainly of large, crude, oval-shaped granite batholiths protruding through Grenville (Archean) strata. These batholiths are arranged with a prevailing trend north 30 degrees east, and the strata usually lap over on them with quaquaversal dips, generally not at very high angles. A structure section across the region would not reveal a very highly folded arrangement of the rocks. It seems not at all unreasonable to interpret this moderate deformation as having resulted mainly from the upwelling of the batholithic magma bodies under conditions of not more than slight lateral pressure.

Structure sections through both the Rainy Lake (Lawson, 1913) and Geneva-Sudbury (Tanton, 1913) districts of Ontario show that the older pre-Cambrian rocks are there considerably folded, but certainly not severely folded. In a number of studied areas of Ontario and Quebec, writers record rather persistently steep dips, while for other areas the degree of deformation is not stated in the publications.

In a report on the "Selkirks and Interior Plateau of British Columbia," Daly⁵ emphasizes the fact of the remarkable freedom of the Shuswap (pre-Beltian) series from deformation.

⁴ F. D. Adams and A. E. Barlow: *Geol. Sur. Can., Mem. 6*, 1910.

⁵ R. A. Daly: *Geol. Sur. Can., Guide Book No. 8*, 1913, p. 153.

In a very recent paper,⁶ dealing with the southernmost Rocky Mountains of Canada, MacKenzie says:

"From the earliest pre-Cambrian known until at least the beginning of the Tertiary, the accumulation of sediments proceeded without interruption by pronounced deformation, varied from time to time by broad and relatively slight oscillations which caused local erosion and resulted in disconformities."

In the eastern Cordilleran district of the United States earlier pre-Cambrian rocks often show steep dips, but these rocks have usually been more or less intimately intruded by igneous material, which, in part at least, may have been the main cause of the steep dips.

Throughout the Appalachian and western New England regions the pre-Cambrian rocks are more or less highly folded and associated with intrusives, and it is doubtful, as pointed out beyond, whether these rocks were subjected to more than very moderate compression prior to the severe Paleozoic deformation.

From the above statements we may therefore conclude that various portions of the earlier pre-Cambrian rocks have been folded little, if any at all; that various portions have been only moderately folded; that various portions have been highly folded; and that still other portions are not proved to have been much folded in pre-Cambrian time. In many cases, even where steep dips are recorded, the writer believes that the deformation may reasonably be explained as a direct result of magmatic intrusion and injection, accompanied by not more than moderate compressive forces.

Barrell,⁷ who has advocated a similar explanation, says:

"The gnarled and twisted rocks of the Archean speak of the presence beneath them of molten magmas rather than of an enormous degree of compressive forces upon them."

For the reasons given, the writer can not subscribe to the statement that the earlier known pre-Cambrian rocks were everywhere highly compressed and folded in pre-Cambrian time.

POST-CAMBRIAN FOLDING OF PRE-CAMBRIAN ROCKS

In any discussion of pre-Cambrian folding, discrimination must be made between those rocks which were folded in pre-Cambrian time and those which were folded in later time. In many cases this can be done, and often earlier and later pre-Cambrian deformations can be recognized. This is particularly true of many parts of the Canadian Shield. In other

⁶ J. D. MacKenzie: Transactions Royal Soc. Can., vol. 16, 1922, p. 98.

⁷ J. Barrell: Jour. Geol., vol. 23, 1915, p. 511.

cases such distinctions have not as yet been very satisfactorily made out, as, for example, in the Appalachian-Piedmont region and western New England, where Paleozoic deformation has very largely overwhelmed and obscured whatever pre-Cambrian folding there may have been. Structure sections in various United States Geological Survey folios illustrating the region from New Jersey to Georgia show both pre-Cambrian and Paleozoic rocks to have been folded in similar manner apparently by the same force or forces.

Mr. Arthur Keith has, however, recently told the writer that there is evidence for at least some pre-Cambrian deformation. In the Nantahala, North Carolina, folio Keith says:

"The various deformations (Precambrian and Paleozoic) have greatly changed the aspect of the rocks (Cambrian and pre-Cambrian)—so much so, in fact, that the original nature of some of the oldest formations can be at present only surmised."

Also:

"Structures in the Archean uplift in the southeastern part of the quadrangle do not differ radically from those in the sediments."

But in regard to the pre-Cambrian Carolina and Roan gneisses, he says that they have "passed through two deformations, one producing the foliation and a second folding the foliation planes." Since these gneisses were originally probably either granites or injection gneisses, is it necessary to assume that their foliation was produced by severe compression? Could not this structure be either a primary foliation or a magmatic injection structure produced under conditions of only very moderate lateral pressure, according to the principles set forth in the writer's paper⁸ already referred to?

Professor Bascom in a recent letter says, in regard to southeastern Pennsylvania, that the

"pre-Cambrian rocks were folded (in pre-Cambrian time), but I am not prepared to say 'notably'; close folding can not be proven; there is general divergence of strike in some places over long distances; folding about igneous intrusions of pre-Cambrian age can be positively differentiated from Paleozoic folding, of course relatively local in character. . . . Of course, the very intense Paleozoic folding now dominates and obscures all previous folding."

From these statements it seems reasonable to believe that such pre-Cambrian deformation as can be made out may have been largely or wholly caused by the intrusives without severe compression of the region.

⁸ W. J. Miller: Jour. Geol., vol. 24, 1916, pp. 600-612.

For western New England the general situation seems to be somewhat similar to that of the Piedmont district. In both of these regions the pre-Cambrian rocks were much folded during Paleozoic time, but there seems to be little, if any, positive proof that they were very notably folded in pre-Cambrian time.

In Wisconsin and Minnesota deformation of older pre-Cambrian rocks may generally be distinguished from that of the younger pre-Cambrian, and almost undisturbed Cambrian strata rest on the pre-Cambrian.

In the Rocky Mountain and Colorado Plateau districts of the western United States two sets of pre-Cambrian rocks, representing either one or two times of pre-Cambrian deformation, have been recognized in relatively few places, as, for example, in the Grand Canyon of Arizona; Needle Mountains, Engineer Mountain quadrangle, and Rocky Mountain Park, Colorado, and Three Forks and Little Belt Mountains, Montana. In a few districts, as, for example, Pueblo, Colorado, and Fort Benton, Montana, Archean pre-Cambrian rocks only are described. Algonkian rocks only are described as occurring in a number of districts, as, for example, Telluride, Rico, and Ouray, Colorado; Hartville, Wyoming, and Philipsburg, Montana. In most of the described regions, however, the pre-Cambrian is not differentiated, as, for example, Georgetown, Silver Cliff, Pikes Peak, and Park Range, Colorado; Medicine Bow, Encampment, Laramie-Sherman, and Bald Mountain-Dayton, Wyoming; Cœur d'Alene, Idaho; Bradshaw Mountains, Clifton, Globe, and Bisbee, Arizona, and Van Horn and Llano-Burnet, Texas.

In most of the districts of the Rocky Mountain-Colorado Plateau region just mentioned the pre-Cambrian rocks, in part at least, are definitely known to have been more or less deformed in pre-Cambrian time. In some of the districts the Algonkian strata are either not very notably folded, as, for example, Grand Canyon, Arizona, and near Marysville, Montana, or their folding was largely or wholly developed by post-Cambrian disturbances, as, for example, Philipsburg and Three Forks, Montana, and Ouray, Colorado.

Enough facts have now been presented to show that, in any attempt to work out the folded structures of pre-Cambrian age in North America, it must be recognized that by no means all pre-Cambrian rocks, and not even all the earlier ones, have been severely folded, and that a careful discrimination must be made between pre-Cambrian rocks folded in pre-Cambrian time and those folded later. Unless such a distinction can be made, the existing strikes of folds of pre-Cambrian rocks afford no trustworthy criteria in regard to pre-Cambrian diastrophism.

LACK OF RECORDS FOR MUCH OF THE CONTINENT

Vast areas of North America contain few, if any, outcrops of definitely known pre-Cambrian rocks, as, for example, Alaska, Mexico, the Cordilleran region and plains of western Canada, the western Cordilleran region of the United States, the Great Plains, much of the Mississippi Valley, and the Atlantic and Gulf coastal plains. Even within the vast pre-Cambrian area of Canada observations on the rock structures are widely scattered, and there are hardly any for its northern half.

Still another difficulty lies in the fact that in many areas containing pre-Cambrian rocks descriptions of the rocks are very brief, and one often looks in vain for such structural data as the strike of folds and foliation.

This lack of evidence in regard to so much of the continent is a very serious difficulty in the way of trying to determine any possible uniformity or systematic arrangement of trend-lines or strikes of folding and foliation of pre-Cambrian age, the more so because, where such strikes have been rather definitely determined in many districts, they seem to show anything but a systematic or uniform grouping (see accompanying map).

SIGNIFICANCE OF THE DURATION AND SUBDIVISIONS OF THE PRE-CAMBRIAN

It is quite generally recognized that known pre-Cambrian time was tremendously long, probably fully as long as all later time put together. It is also generally agreed that there were various periods of more or less vigorous diastrophism, often accompanied by folding, in pre-Cambrian time, and that diastrophic forces were, as a rule, less pronounced in the later than in the earlier pre-Cambrian. Also, in a very general way, the pre-Cambrian has commonly been divided into two great eras—Archeozoic and Proterozoic. It must, however, be recognized that these two subdivisions by no means represent such definite time intervals as do the Paleozoic, Mesozoic, and Cenozoic eras. Where, for example, both the Archeozoic and Proterozoic rocks occur in a given region, the line of separation may represent a time many millions of years younger or older than the line separating rocks similarly classified in some other region. A perusal of the literature shows that this is a real difficulty in the classification of the pre-Cambrian rocks, even of the Canadian Shield itself, in regard to which various writers are by no means in agreement as to where the line (unconformity) between the older and the younger pre-Cambrian rocks should be placed, and some writers even argue for more than two important groups of rocks.

In many districts in North America the oldest rocks are simply classed as "pre-Cambrian" not only because there is no valid reason for subdividing them, but also because they can not, with any degree of assurance, be classified as either Archeozoic or Proterozoic. Again, within groups of rocks classed as Proterozoic, the number of important structural breaks varies from none to several, and we have not as yet devised a satisfactory method of correlating the subdivisions in one region with those in a separate area far from it. These are all fundamental facts which must be duly considered in any effort to work out the pre-Cambrian structural history of the continent.

Evidence has already been presented to show that not all pre-Cambrian rocks were highly folded in pre-Cambrian time. All through his paper, however, Ruedemann considers "pre-Cambrian worldwide folding" to be an established fact. He also recognizes the great length of pre-Cambrian time, and believes that the assumed worldwide pre-Cambrian folding (pages 129-134) originated either from a "long-time, gradual extension of local folding" or from a worldwide simultaneous folding, more likely the former. In any case he advocates the hypothesis that the pre-Cambrian continent of North America responded to *universal folding as a unit* (page 75), and that the diastrophic agencies developed a *uniformity of trend* of the folded structures as indicated on the accompanying map. The writer dissents from all three factors of this hypothesis for the following reasons:

First. Evidence has already been presented to show that even very old pre-Cambrian rocks have not been *universally* notably folded.

Second. With regard to the proposition that the continent reacted as a *unit* against folding agencies, it seems to the writer that such a conclusion is not warranted by the facts. In the light of our great uncertainties concerning the subdivisions and correlation of subdivisions of pre-Cambrian time, is it not dangerous to lump together the sum of many local foldings of various times (geologic ages apart) as if they represent a continuous, general process? If they do not represent such a continuous, general process, then the sum total of all pre-Cambrian folded structures can not possibly be used to represent the configuration of the continent as a unit. In this connection we should think of the various great diastrophic movements, widely separated in space and time, which are definitely known to have taken place in North America in post-Cambrian time. During this vast lapse of time, probably no longer than that of the pre-Cambrian, the continent has undergone many important diastrophic changes. As emphasized by Schuchert in his presi-

dential address at the 1922 meeting of the Geological Society of America, the great scenes of diastrophism during the Paleozoic were in the eastern part of the continent, while in later geologic time the scenes shifted to the western part. Nor can it be maintained that these foldings developed progressively in any direction or directions, or, in other words, that successive strips of the continent were affected, as suggested for the pre-Cambrian by Ruedemann, because, for example, the great Rocky Mountain disturbance, far within the continent, took place well after the Sierra Nevada folding along the margin of the continent. Furthermore, in post-Cambrian time much of North America has been unaffected by any notable folding. This is an important fact in view of Ruedemann's advocacy of universal pre-Cambrian folding. In brief, North America in post-Cambrian time has been only very locally affected by notable foldings, mostly widely separated in space and time. Surely, then, the continent has not, in post-Cambrian time, responded to universal, long-time folding as a unit! In the absence of anything like definite facts to the contrary, is it not reasonable to believe that similar conditions obtained during the vast lapse of pre-Cambrian time?

Third. In regard to Ruedemann's conclusion that North America responded uniformly to the diastrophic forces of folding, evidence will now be presented at some length to show that such was not the case.

OBSERVED STRIKES OF PRE-CAMBRIAN FOLDING AND FOLIATION

GENERAL STATEMENT

The map accompanying this paper shows two features—the general trend-lines of pre-Cambrian folding and foliation as observed by Ruedemann and many of the more important actually observed strikes of pre-Cambrian folds and foliation. Several hundred pieces of literature dealing with regions in which pre-Cambrian rocks occur were examined in order to secure the data for the strikes recorded on this map. In many publications the necessary structural data are wholly lacking. Further search would bring to light a considerable number of other observations, but these would mainly only fill in detail without essentially altering the situation as represented on the map. Folding and foliation of pre-Cambrian rocks almost certainly produced after pre-Cambrian time are not recorded, except in a few cases by short broken lines, as in the Appalachian region and a few other places. In a few of the recorded cases post-Cambrian diastrophism may have been an important factor, but at most in only a few.

LABRADOR, NOVA SCOTIA, AND NEW BRUNSWICK

In northern Labrador (A. P. Coleman, 1921) many observations show a strongly predominant north-northeast strike of the pre-Cambrian rocks, or at right angles to Ruedemann's trend-lines.

Late pre-Cambrian rocks in southern Nova Scotia (Faribalt, 1913) are closely folded with east-west strike, thus making a high angle with Ruedemann's lines.

Several narrow belts of pre-Cambrian rocks in southern New Brunswick (Young, 1913) show a general northeast strike, but this seems to be wholly due to infolding with Paleozoic strata, and data regarding the pre-Cambrian are lacking.

EASTERN CANADA

Quebec.—In Quebec and Ontario there is probably more of a tendency for Ruedemann's trend-lines to harmonize with actually observed strikes of folds and foliation than in any other large part of the continent, but even there the divergences are often conspicuous.

In the general region about half way between James Bay and Lake Saint John (H. C. Cooke, 1919), in the Opiwaki, Fathers Lake, Windy Lake, Eau-Jaune, Kenoniska, Mettagami, Pontiac, and Brock areas, the whole region appears to have been folded (but by no means everywhere severely) with a general east-west to south 75 degrees east strike, but with some important local variations.

In southern Argenteuil County, about 50 miles west of Montreal (M. E. Wilson, 1917), there is a persistent strike of north 10 to 30 degrees east.

The Lake Saint John area (Dresser, 1916) shows a general strike about north 10 degrees west for the older pre-Cambrian rocks and about north 30 to 40 degrees east for the younger ones, the older structure lines in this case being almost at right angles to Ruedemann's trend-lines.

In the large Harricanaw area (Tanton, 1919), about half way between James Bay and Lake Temiskaming, most of the strikes range from north 20 degrees west through northwest to nearly east-west.

Ontario.—The large, carefully studied Haliburton-Bancroft area (Adams and Barlow, 1910) of southeastern Ontario shows a general north 30 degrees east trend of batholiths and folding, though there are many local variations in the folding, which is of only a moderate degree.

The Geneva-Sudbury area (Tanton, 1920) shows considerable folding with a northeast strike.

Not far north of Sudbury, however, in the Onaping area (Collins, 1917), the structure lines persistently run northwest, or at right angles

not only to those of the Geneva-Sudbury area, but also nearly at right angles to Ruedemann's lines.

Collins⁹ says that the generally assumed northeast structural trend of Quebec and Ontario is, after all, not so persistent, and that probably, as work proceeds, "many important irregularities like that in the Onaping area will be discovered in the regional trend." A glance at the accompanying map plainly bears out this suggestion.

In northern Ontario both the Amisk Lake area (Bruce, 1918) and the Matachewan area (Cooke, 1919) show a north 60 to 70 degrees east strike of folds.

The Rainy Lake district (Lawson, 1913) of southwestern Ontario shows ordinary folding of two great sets of pre-Cambrian rocks with a general north-northeast strike.

In the Lake of the Woods region (Parsons, 1913) the general strike of older pre-Cambrian rocks is north 60 to 80 degrees east.

Manitoba.—The Reed-Wekusko area (Alcock, 1920) of northern Manitoba shows a north 35 degrees east strike; also, in northern Manitoba, the Ospwagan Lake and the Southern Indian Lake areas (Alcock, 1920) show a general northeast strike. All three of these strikes cut across Ruedemann's lines at high angles. The Knee Lake district (Bruce, 1920) of central Manitoba mostly shows steep dips and strikes ranging from east-west to southeast.

WESTERN CANADA

Very few observations on the structure of the pre-Cambrian rocks of western Canada seem to be recorded, and these show little or no real harmony with Ruedemann's lines. In the Athabasca Lake region (Camsell and Malcolm, 1919) the older pre-Cambrian rocks have high dips with northeast strike at the lake and a strike varying from north-south to northwest on Taltson River. The younger pre-Cambrian rocks are little disturbed. Between Athabasca Lake and Great Slave Lake (Camsell, 1916) pre-Cambrian rocks range in strike from northwest through north-south to northeast, with an average north-south trend.

In the Selkirk Mountains and Interior Plateau (Daly, 1913) of southern British Columbia a widespread earlier pre-Cambrian (Shuswap) series is remarkably little deformed, and its strike is north 70 degrees east, or almost at right angles not only to the trend of the Rocky Mountains, but also to Ruedemann's lines.

In the southernmost Rockies of Canada (MacKenzie, 1922) a remarkable fact is that earlier pre-Cambrian rocks remained practically unde-

⁹ W. H. Collins: Geol. Sur. Can., Mem. 95, 1917.

formed (indicated by circle on the map) until the Rocky Mountain folding of the early Tertiary.

Of the relatively few definitely known pre-Cambrian structure lines within the vast area of the western half of Canada, therefore, only part of those by Camsell in the Athabasca Lake region are even approximately in harmony with the trend-line announced by Ruedemann.

EASTERN UNITED STATES

Northern New York.—The writer has for many years been making detailed studies throughout the Adirondack Mountain region, and, as already pointed out in this paper, he does not believe that this whole region of earlier pre-Cambrian rocks was ever very notably folded. Neither does the writer believe that there is a distinct northeast structural trend throughout the district. The strikes, which are mostly magmatic flow structure lines and partly foliation of tilted blocks of metamorphosed strata, are exceedingly irregular throughout the Adirondacks. The actual facts and their significance are dealt with at some length in a paper¹⁰ published a few years ago.

The writer agrees with Ruedemann that the area from the northwestern border of the Adirondacks to the Thousand Islands has probably been more or less notably folded with a general northeast trend, but this area is really outside of the Adirondack district, which is 120 miles across and in which the structural conditions are different. It is but necessary to glance at the New York State Museum geologic maps made by the writer and others, representing many portions of the region, in order to realize that the facts do not warrant the conclusion that the pre-Cambrian rocks of the Adirondacks show a distinct northeast folded structure. As already mentioned, Collins says that a northeast structural trend through Quebec and Ontario is not nearly as persistent and clearly defined as has generally been assumed. This idea of persistence of trend appears to have originated many years ago, when knowledge of the pre-Cambrian structure of eastern Canada and northern New York was largely confined to the Saint Lawrence Valley region, in which a northeast trend does prevail.

New England.—In both western and southeastern New England belts of pre-Cambrian rocks show a general north-south trend, but this structure has largely or wholly resulted from a high degree of infolding with Paleozoic strata; and so this structure has no significance in our present discussion. Mr. Arthur Keith has, however, recently stated to the writer

¹⁰ W. J. Miller: Jour. Geol., vol. 24, 1916, pp. 587-612.

that there is some evidence that, in western New England, structure lines in the pre-Cambrian rocks trend somewhat west of north. If so, such a trend makes a high angle with Ruedemann's lines.

Appalachian-Piedmont region.—The Appalachian-Piedmont region, from southwestern New York to Georgia, contains large bodies of pre-Cambrian rocks; but these have been so highly deformed during Paleozoic time, and in part even so closely infolded with metamorphosed Paleozoic strata, that the pre-Cambrian structure lines have been largely obscured, if not in many places wholly obliterated by the Paleozoic deformation. Thus, in the Trenton, New Jersey, Quadrangle (Bascom, 1909) the pre-Cambrian gneisses are folded along with Paleozoic strata, and strike north 60 to 80 degrees east with them.

According to Miss Bascom:

"The prevailing structural features of the Piedmont Plateau are major folding of the Appalachian type, forming anticlinoria and synclinoria which extend for long distances."

In their description of the Washington, D. C., Quadrangle, Williams and Keith state that "typical Appalachian folds are to be seen in the Piedmont region." Similar statements are made by Keith in various later folios.

In the Franklin Furnace, New Jersey, folio Spencer says:

"No estimate can be given of the extent to which the attitude of the ancient rocks was modified by the earth movements which folded and faulted the Paleozoic formations."

The present general northeast trend of the pre-Cambrian rocks of the Appalachian-Piedmont region cannot, therefore, be assumed to represent pre-Cambrian trend-lines. If, however, the writer, in a recent conversation, properly understood Mr. Keith, who knows the general region so well, there is definite evidence that real pre-Cambrian structure lines are still preserved, and that these run in general more nearly north-south than northeast (see accompanying map). Such being the case, the actual pre-Cambrian structural trend makes a considerable angle with the lines shown on Ruedemann's map.

MINNESOTA, WISCONSIN, AND MICHIGAN

Pre-Cambrian structures are well preserved in portions of these States where the great iron ore districts have been carefully studied. Both the Mesabi and Vermilion districts of Minnesota show strikes of about north 70 degrees east for many miles, and the newer Cayuna district (southwest of Mesabi) has a structural trend of north 50 degrees east. The struc-

tural trend of the Penokee-Gogebic district in Michigan-Wisconsin is north 30 degrees east; of the Marquette, Michigan, district is east-west, and of the Menominee, Michigan, district is west-northwest.

Older and younger pre-Cambrian rocks of north-central Wisconsin (Weidman, 1907) show mostly steep dips with very variable strikes, but a general northeast trend seems to predominate. In south-central Wisconsin (Weidman, 1904) late pre-Cambrian quartzite forms an east-west synclinalorium 20 miles long.

From the evidence presented, it is clear that in the Minnesota-Wisconsin-Michigan region three districts show strikes in close conformity with Ruedemann's trend-lines, while in five districts the strikes make high angles with those trend-lines, thus exhibiting sharp differences within this area.

MISSOURI AND SOUTH DAKOTA

In the whole vast area, about one million square miles, between the Appalachians and the Rockies, scarcely anything is known about the pre-Cambrian rocks structures, so that any attempt to draw pre-Cambrian structure lines through this area must be largely guesswork.

At Pilot Knob, Missouri (Pumpelly, 1873), a relatively small area of pre-Cambrian rock shows an average dip of only 13 degrees and a strike north 50 degrees west.

In southeastern South Dakota (Todd, 1903) later pre-Cambrian quartzites in a number of small areas lie in almost horizontal position (shown on map by a circle), and so they are of practically no significance in our discussion.

The Black Hills of South Dakota consist of a large core of pre-Cambrian folded strata and igneous rocks (presumably Algonkian) in which the pre-Cambrian structures are well preserved. The general strike seems to be about north-south (Van Hise, 1890), but there are notable variations, as, for example, in the southern part (Newton, 1880), where there is a northwest strike, and in the northern part (Frazer, 1898), where mica schists strike northeast.

TEXAS

Two areas in Texas furnish reliable pre-Cambrian structural data: One is the Lano-Burnet district (Paige, 1912), in the central part of the State, where pre-Cambrian (Algonkian?) strata are distinctly folded with a northwest strike. The other is the Van Horn district (Richardson, 1913), in the western part of the State, where pre-Cambrian strata strike northeast. In one of these cases the trend corresponds to Ruedemann's lines, while in the other it is at right angles to them.

ARIZONA AND NEW MEXICO

In the Shinumo Quadrangle (Noble, 1914) of the Grand Canyon district steep-dipping Archean schists exhibit a general northeast strike, with local variations. Tilted and faulted, but not folded, Algonkian strata rest on the schists.

The Bradshaw Mountains of central Arizona (Jaggard and Palache, 1905) contain pre-Cambrian rocks which were highly folded, with a general north-south strike, before Paleozoic time.

The Globe district (Ransome, 1904) shows an extensive development of steep-dipping pre-Cambrian schist with a northeast strike. Ransome says:

"It is noteworthy that the strike of the schistose cleavage runs nearly at right angles to the dominant trend of the present mountain ranges of the region."

Much faulted, but little folded, Paleozoic strata rest on the schists.

A small area of steep-dipping pre-Cambrian schist and granite in the Clifton, Arizona, region (Lindgren, 1905) shows varying strikes, ranging mostly between east-west and north 30 degrees east.

The Bisbee area (Ransome, 1904), in the southeastern corner of Arizona, contains steep-dipping pre-Cambrian schists with a dominant strike about north 25 degrees east. Only moderately folded Paleozoic strata rest on the schists.

But little information regarding pre-Cambrian structures in New Mexico seems to be available. In the northern part of the State there are several belts of pre-Cambrian rocks, but their north-south trend does not necessarily indicate such a pre-Cambrian structural trend. Thus, in regard to the schists and granite of the Cimarron belt Stevenson (1881) says that "the dips of the Archean rocks are much confused."

For the most part, then, in Arizona and New Mexico, the definitely known pre-Cambrian structural trend-lines make high angles not only with the trend-lines as shown on Ruedemann's map, but also with the general trend of the Rocky Mountains.

NEVADA AND UTAH

Few reliable observations on pre-Cambrian structures appear to be available for Nevada, where definitely known pre-Cambrian rocks are not extensively developed. The West Humboldt Range (Emmons and Hague, 1877) shows steep-dipping schists and gneisses with strike north 38 degrees east.

The Snake Range of eastern Nevada (Weeks, 1907) contains steep to moderately steep dipping quartzite with a west-northwest strike.

Pre-Cambrian rocks are not extensively exposed in Utah, and satisfactory structural data are scarce. In Big Cottonwood Canyon (Emons, 1877) of the Wasatch Mountains near Ogden, pre-Cambrian quartzites and schists, with rather high dips, strike northeast, and in Little Cottonwood Canyon schists strike northwest. In the small Farmington (Hague, 1877) area of the same general region, pre-Cambrian rocks strike about north-south.

According to Blackwelder (1910), a considerable body of Algonkian strata lies within the Wasatch Mountains east of Ogden, but structural lines within it are not reported.

The main body of rock in the midst of the Uinta Range is late pre-Cambrian quartzite only very moderately disturbed and with a general east-west strike of post-Cambrian origin.

It is, therefore, clear that the few pre-Cambrian structure lines above recorded from Nevada and Utah show widely varying strikes, mostly notably divergent from Ruedemann's trend-lines.

COLORADO

This State furnishes an unusual number of records of pre-Cambrian structure lines from both large and small areas.

In the vicinity of Silver Cliff (Cross, 1896) pre-Cambrian gneisses strike northeast.

Small areas of pre-Cambrian (Archean?) schists near Pueblo Gilbert, 1897) show strikes varying from north-south to northwest, with little disturbed Cretaceous strata resting on them.

In the Rico Quadrangle (Cross and Ransome, 1905) a small area of pre-Cambrian schist with steep dips strikes east-west, while within a few miles of it folded Algonkian strata show strikes varying from north 10 to 30 degrees east, with scarcely folded Paleozoic strata on them.

Both Archean and Algonkian rocks are well represented in the Needle Mountains Quadrangle (Cross and Howe, 1905), the general strike of the former swinging from a little east of north to nearly east-west, while the latter (Algonkian) ranges in strike from east-west to west-northwest. Both sets of rocks were notably folded before the opening of the Paleozoic.

Steep-dipping Algonkian strata in the Óuray Quadrangle (Cross and Howe, 1907) show an average east-west strike, but part or all of this deformation belongs to post-Cambrian time.

In the Telluride Quadrangle (Cross, 1899) a small area of rather steep-dipping Algonkian strata exhibits a well preserved strike north 65 degrees west.

The Engineer Mountain Quadrangle (Cross, 1910) contains Archean gneiss and schist in its southeastern part with strikes varying from east-west through northeast to nearly north-south, and Algonkian strata with nearly east-west strike in its northeastern part.

The Pikes Peak area (Cross, 1894) contains some pre-Cambrian gneisses with a north-northwest strike of foliation.

Pre-Cambrian rocks in the Georgetown Quadrangle (Ball and Spurr, 1905) exhibit an excellent schistosity, with a prevailing east-west strike.

Earlier pre-Cambrian gneisses in Rocky Mountain Park show a general north-south strike of foliation, while steep-dipping Algonkian strata in Thompson Canyon, just east of the park, strike about east-west.

The southern portion of the Park Range (Van Hise and Leith, 1909) of northern Colorado consists of pre-Cambrian rocks with a prevailing north-south strike, which changes to a general east-west strike in the northern portion of the range.

WYOMING

Pre-Cambrian structural data are obtainable for several districts in the southeastern one-fourth of this State.

The Encampment district (Spencer, 1904), near the middle southern border of the State, shows a large development of pre-Cambrian strata with a distinct strike nearly east-west for over 20 miles. This strike is the same as in the adjacent Park Range of Colorado.

In the Medicine Bow Range (Hague, 1877) a large development of steep-dipping Archean gneiss, schist, and quartzite strikes about north 20 degrees east.

In the Laramie-Sherman Quadrangle (Darton and Blackwelder, 1910) of southeastern Wyoming pre-Cambrian gneiss and schist are well developed, with a prevailing strike north 70 degrees east.

The Hartville district (W. S. Smith, 1903), in the eastern part of the State, contains Algonkian schist, limestone, and quartzite with practically vertical dips and a generally nearly east-west strike.

A large area of pre-Cambrian granite is exposed in the Big Horn Mountains (Darton, 1906). It is devoid of foliation, and so gives no clew to the pre-Cambrian structure of this region. It is involved, with Paleozoic strata on either side, in a gentle anticlinal structure. This occurrence is of interest, however, because it is such a large body of pre-Cambrian rock which has never been subjected to much pressure.

Pre-Cambrian rocks are extensively exposed in the Wind River Mountains, but not much seems to be known about their structure. In 1879, however, Endlich said:

"The granites are flexed and contorted in every possible direction and contain simple bands of micaceous and chloritic schists which denote the original planes of stratification."

In the Gallatin Range of Yellowstone Park (Hague, 1899) a relatively small area of pre-Cambrian schist shows a general north-south strike.

MONTANA AND IDAHO

There are several areas of pre-Cambrian rocks in the western half of Montana for which more or less structural information is available.

In the Little Belt Mountains (Weed, 1899) an area of Archean has steep dips and a general east-west strike. Resting on the Archean are very moderately folded Algonkian and Paleozoic strata.

A small area of Archean gneiss and schist in the Fort Benton Quadrangle (Weed, 1899) shows steep dips and very variable strikes.

The geological map of the Three Forks Quadrangle (Peale, 1896) shows large areas of Archean gneisses, but their structure is not described. There are also Algonkian (?) marble and schists which were metamorphosed and folded (structural data not given) before the deposition of an unaltered Algonkian sedimentary series, which latter is intricately infolded with Cambrian and Cretaceous strata.

In the Marysville district (Barrell, 1907) near Helena, Algonkian strata are only gently folded with very irregular strikes. The prevailing strike seems to be northwest, but Barrell speaks of a cleavage structure with a northeast trend.

In the Philipsburg Quadrangle (Calkins and Emmons, 1913) Algonkian strata are extensively exposed with exceedingly variable strikes and with only a general parallelism with the late Cretaceous folds, so that in part the folding may be of pre-Cambrian age.

The great body of Algonkian strata in Glacier Park has a long, wide, gentle synclinal structure, with nearly north-south strike, but this structure was probably developed at the time of the thrust-faulting in the early Tertiary.

The Cœur d'Alene district of Idaho (Ransome and Calkins, 1908) contains much pre-Cambrian stratified rock notably folded with very irregular strikes, but with a northwest trend somewhat prevalent.

CONCLUSIONS REGARDING THE CORDILLERAN REGION

From the data above presented it is evident that there is no predominant pre-Cambrian structural trend through the Cordilleran region of the United States approximately parallel (north-northwest) with the trend of the Rocky Mountains. A glance at the accompanying map will

show that decidedly more of the pre-Cambrian trend-lines run from east-west to about northeast rather than approximately north-northwest. It is, therefore, a very significant fact that the prevailing direction of pre-Cambrian folding and foliation is *across* the Cordilleran region rather than *parallel* with it. Considering this fact, together with the meager structural evidence from western Canada and the practical absence of definite evidence from Alaska and Mexico, it is clear that there are no sufficient grounds for advocating a general north-south trend of pre-Cambrian folds and foliation through western North America, as has been done by Ruedemann. This matter is all the more significant when it is realized that the western half of the whole continent is involved!

GENERAL CONCLUSIONS

Some of the main conclusions in regard to the pre-Cambrian folded and foliated structures of North America which seem to be warranted as a result of the evidence presented in this paper are as follows:

1. The older known pre-Cambrian rocks of North America have not been universally intensely folded, as has heretofore been commonly assumed. In some districts they have never been more than very moderately folded, and in other districts they have been moderately or highly folded only since pre-Cambrian time. In many districts they were, however, highly deformed in pre-Cambrian time. In many cases the probability of the development of steep dips and more or less folding through the agency of magmatic intrusion, under the influence of but little lateral pressure, should be considered.

2. In any attempt to decipher pre-Cambrian diastrophism in North America, careful discrimination should be made between folded structures of pre-Cambrian rocks developed in pre-Cambrian time and those subsequently produced. In many districts this has not been done and in some cases it is impossible.

3. Because of the vast length of time involved and the great uncertainties of subdivision and correlation of pre-Cambrian rocks in various parts of the continent, we are still in the dark in regard to the number, extent, severity, and correlation of crustal deformations of pre-Cambrian time. More particularly, the facts do not warrant the conclusion that there was a great continent-wide so-called "Laurentian Revolution" marking the close of a rather definite portion of pre-Cambrian time.

4. The plotting of many definitely recorded strikes of pre-Cambrian folding and foliation (see accompanying map) does not indicate "a grand and simple curvature," changing from a northeast direction in the eastern part of the continent through east-west in the interior to approxi-

mately north-south in the western part of the continent, as advocated by Ruedemann.

5. There is not sufficient warrant for a statement that North America reacted as a "unit against the diastrophic forces active in pre-Cambrian time," as advocated by Ruedemann. On the contrary, because of notable variations in structural trend, even in local portions of the continent (see map), and because of the localization of orogenic forces, both in space and time, during the very long post-Cambrian history of the continent, it is more reasonable to believe that similar localization obtained during pre-Cambrian time.

5. The absence of pre-Cambrian structural data from vast areas (fully one-half) of North America causes a large element of uncertainty to enter into any attempt to generalize with regard to the trend-lines of pre-Cambrian folds and foliation.

DISCUSSION

Dr. R. Ruedemann sent the following letter, which was read in opening the discussion:

It is just as well that Professor Miller attracts attention to my paper on the "Existence and Configuration of pre-Cambrian Continents" by attacking its premises. This is always the surest means of keeping a new-born idea from the limbo of the still-born and forgotten.

The points which Professor Miller proposes to raise, according to the program, refer to premises that had been recognized by me as the ones that needed protection and that therefore have been frankly stated in the paper to be open to discussion and the evidence for which has been fully presented, as far as the limited space allowed.

The first point is that the Archean basement complex in North America has not everywhere undergone severe metamorphism. This is, as far as I can see, of no critical importance for the solution of the problem involving the presence and configuration of the pre-Cambrian continents and may, therefore, be passed without comment.

The second point is that the Archean basement complex has not been universally intensely folded. In this regard Professor Miller disagrees, as far as the Adirondacks, his field of study and experience, is concerned, with all the other geologists that have worked in the Adirondacks, and that fact is set forth in my paper. As my conclusions must be based, of course, on the consensus of authors and not on a single dissenting view, the latter, however interesting, is of no account in this matter.

The third point is that "the pre-Cambrian folding does not exhibit such uniformity of direction as has been recently advocated" (by the writer). The claim that the folding is uniform in its grand outlines is based on the evidence gathered from the pre-Cambrian literature of the world there cited and will have to stand or fall with the correctness of the many observations quoted.

It may be added that more corroborative literature is at hand, and that articles which have appeared since the paper was written nicely fall in, in the pre-Cambrian trends given, with those merely inferred for the regions in question. It should also be pointed out, as has been fully done in my paper, that while the author speaks principally of the fold directions, the trend-lines of the pre-Cambrian rocks there under discussion comprise not only the fold directions, but also the direction of the foliation, schistosity, and of the major axes of the batholiths, all of which phenomena form a causally connected group.

It should be remembered that these criteria, in a paper dealing with their continental or even world-wide order of magnitude, can not be judged fairly and properly from the study of a very limited area in the Adirondacks alone, however thoroughly this may have been done.

Professor Miller further points out that "the vast length of pre-Cambrian time and the uncertainties of its divisions, as well as the difficulty in many places of distinguishing rock structures which developed during pre-Cambrian time from those produced by post-Cambrian diastrophism, are antagonistic to any attempt to decipher the pre-Cambrian configuration of the continent." These difficulties are fully recognized in the paper and stated as such; but since also the general parallelism of the greater subdivisions in the different continents, of the northern hemisphere at least, is set forth following the views of Adams, Kemp, Willis, and others, and it is further brought out that the folding and its associated phenomena, as seen now in the pre-Cambrian rocks, is the summation of that of all pre-Cambrian eras and is treated as such; the criticism is beyond the point. Pre-Cambrian and post-Cambrian folding have been carefully separated in the paper, and areas where the latter is evident have been omitted from the discussion.

As the conclusions set forth in my paper are based on a great mass of data scattered in the literature, they must stand or fall, I repeat, with the correctness of the many observations there recorded and with those yet to be made. All that I, therefore, ask is that these conclusions be given a fair and unbiased trial by those engaged in the study of pre-Cambrian geology and paleogeography, and I have no doubt that such will be granted by the great majority of geologists.

Prof. A. P. COLEMAN: The early pre-Cambrian rocks of Canada represent only the foundations of the original mountains. They have batholithic forms and the schistose structures strike in all directions around the great batholiths, but the batholiths themselves generally show an elongation in a direction roughly parallel to the edges of the pre-Cambrian Shield. In northern Ontario the structures run usually from north 50 to 80 degrees east. The ancient mountain ranges overlying the batholiths probably ran in the direction shown by this trend in the elongation of the batholiths.

Miss MARGARET FULLER: The results of a recent detailed field study of the pre-Cambrian geology of the Front Range in Colorado, from the

Continental Divide eastward through the Valley of the Big Thompson River to the foothills, may shed some light on the question of the pre-Cambrian structure of the Cordilleran area. The pre-Cambrian consists of a series of highly metamorphosed sediments, mainly schists, intruded by two granites, with their accompanying wealth of pegmatites. The structure is one of numerous batholiths, which have arched and metamorphosed the sediments in a long north-south belt, the more intense metamorphism being near the center of the range and extending north and south in a belt which grades eastward into a similar north-south parallel belt of less intensely metamorphosed rocks. This would indicate that the original pre-Cambrian structure had been one of linear intrusion lines, arching up a north-to-south area. Similar structure in the region north and west of Colorado Springs suggests the same conditions. Probably the more recent arching, which uplifted the Front Range as it lies today, took place along the old pre-Cambrian line of diastrophism.

Reply by Professor MILLER: I regret that Dr. Ruedemann is not here in person. His discussion, based entirely upon the very meager statements in the abstract of my paper, would, I believe, have been considerably modified had he heard my paper in full.

In his paper (page 75) Dr. Ruedemann states it is an established fact that the Archean basement complex has undergone complete metamorphism. I differ from him on this point, but I agree with him that this matter is not necessarily of critical importance, as shown in my paper.

In the second point of his discussion Dr. Ruedemann implies that my whole field of experience is the Adirondacks, but this is by no means true. He also states that all geologists, except myself, who have worked in the Adirondacks agree to the proposition that the whole Adirondack region has been severely folded. This is hardly a fair statement of the situation, because, in the first place, I myself accepted the idea of severe folding and compression of the region until about ten years ago, when I began to critically examine the field evidence, and, in the second place, some of the workers he cites studied only the northwestern flank of the Adirondack region, where I, too, believe there has been more or less folding; some of the workers have never seriously argued for severe folding, and only two of them have recently really advocated a severe folding of the whole region. Now, as set forth in my paper, it is not a foregone conclusion that the two workers who have advocated severe folding are right and that I am wrong, certainly not in view of the fact that the array of evidence presented by me in 1916 (*Journal of Geology*, volume 24, pages 587-619) has not been attacked. The fact that I have done a greater amount of detailed field-work on the pre-Cambrian rocks of

northern New York than anyone else ought to make my conclusion worth something.

In his third point Dr. Ruedemann defends his conclusion regarding uniformity of direction of pre-Cambrian folding by saying that the conclusion is based upon evidence gathered from an extensive literature on pre-Cambrian geology. My answer is that for years I have been studying this same literature; that I have very recently reviewed hundreds of pieces of this literature, and that I find the evidence pointing to a conclusion different from that of Dr. Ruedemann. Like him, all I ask is that the evidence and conclusions which I present shall be given "a fair and unbiased trial" by students of the pre-Cambrian.

Dr. Ruedemann's statement falls wide of the mark, as my paper plainly shows, when he says that I judge his paper, dealing with a worldwide order of magnitude, "from the study of a very limited area in the Adirondacks alone."

Finally, I do not agree with Dr. Ruedemann that he has carefully separated cases of pre-Cambrian and post-Cambrian folding, as brought out in various parts of my paper.

If, as Professor Coleman states, the pre-Cambrian structures of northern Ontario mainly run from north 50 to 80 degrees east, they certainly are not even approximately parallel to the edge of the Canadian Shield in that general region. Furthermore, on the basis of Coleman's own work, the pre-Cambrian structure of northern Labrador is conspicuously out of harmony with Dr. Ruedemann's trend-lines.

Miss Fuller's observations in a local portion of the Front Range of Colorado do harmonize with Ruedemann's conclusion, as my map shows; but the pre-Cambrian structural trend is there exceptional for much of the Rocky Mountain region of the United States, even that part of the region just to the north, in Wyoming.

GEOTHERMS OF LAKE SUPERIOR COPPER COUNTRY ¹

BY ALFRED C. LANE

(Presented before the Society December 30, 1922)

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SUMMARY

The rate of increase of temperature in the Lake Superior mines averages about one degree per 105 feet, but is greater in depth, about one degree Fahrenheit per 90 feet. While the mean air temperature in Calumet is about 39 degrees Fahrenheit, the mean ground temperature is 43 degrees (42.6 degrees Fahrenheit), owing to the blanketing effect of the snow in winter.

This increase of gradient is due to an increase of surface temperature about 10,000 years ago; for, by taking the gradient below 4,000 feet and producing it to the surface, we find a surface temperature of 32 degrees Fahrenheit, that which the ice bottom may have had. The time since the rise in temperature is found by seeing how much the scale of time may be enlarged in the probability curve connecting the temperature and time for a flow of heat due to a sudden rise of temperature, and yet have the curve lie under one constructed to show the excess of observed temperature over that due to the bottom gradient.

There are indications of a milder climate between the Ice Age and the present.

¹ Manuscript received by the Secretary of the Society February 20, 1923.

The deep gradient of one degree Fahrenheit in 90 feet, equal to one degree centigrade in 49.5 meters, is not so far from that which is normal to the earth, but it is easily explained by the absence of pyrite or signs of any recent exothermal reactions in the rock, by exhaustion of heat from below in early times, by the abnormal thickness of the crust indicated by the observations for isostasy, and the less radioactivity of basic rocks. Reactions leaving CaCl_2 in solution, and hence endothermal, do not need to be inferred.

Lake Superior has no appreciable effect on it, first, because the deeper temperature of Lake Superior (39 degrees Fahrenheit) is practically the same as that at Calumet; secondly, because the gradient near the lake is nearer the normal; and, thirdly, because the lake is too far from Calumet, compared with the difference in elevation, to have an appreciable effect. Similar postglacial heat waves should be and may be noted in the temperature of other deep wells.

HISTORICAL

The first observations on underground temperatures on Keweenaw Point were made back in 1847 and were reported by C. T. Jackson,² and are tabulated in my report on page 759. He rightly assumed 43 degrees as the surface soil temperature—that is, it is probably within one degree of this for the yearly average, which varies a little from year to year, as the table shows. The greatest depth then reached (with no account of the topography) was 236 feet, where the temperature was 45 degrees Fahrenheit. No account has been taken of mean depth from the surface, nor allowance for the topography in any of the measurements.

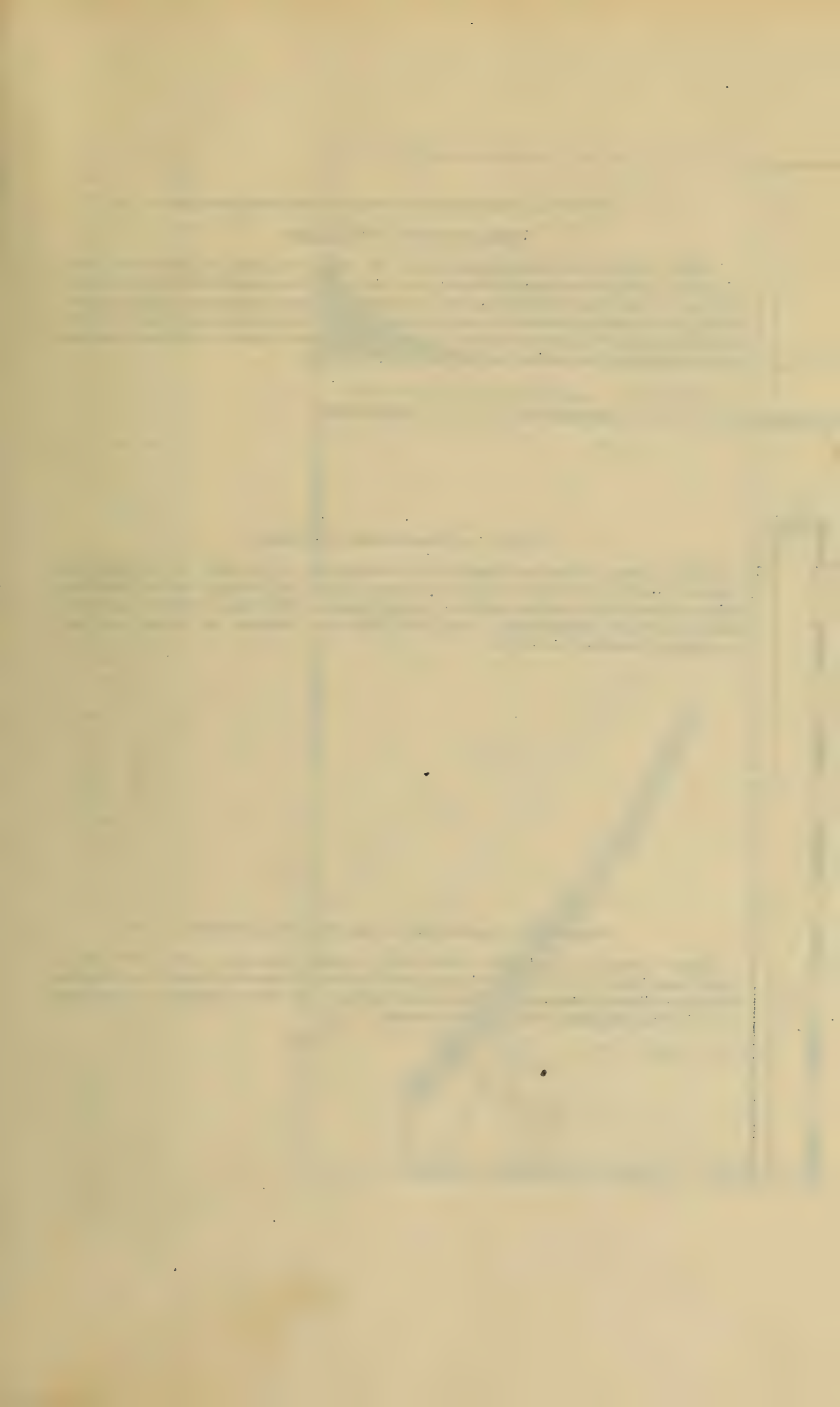
The next important observations were made by H. A. Wheeler.³ Subtracting one degree in 105 from his upper measurements, we get 41.7 degrees Fahrenheit for the initial soil temperature; and, doing the same thing for his lower measurements, we find a temperature of 42.5 degrees Fahrenheit.

In 1894 J. F. Roberts tested the bottom of the Central Mine.

In 1901 I found in the Champion copper mine a temperature of 44 (5 degrees) in the first level, 130 feet below surface, and 45 degrees in the second level, 250 feet down. Making the same deductions of one degree per 105 feet, we have 43.3 degrees Fahrenheit respectively, 42.6 degrees for the surface temperature. In August a strong flow from (as was told me) 80 feet down in Calumet and Hecla hole 10, on section 16,

² Annual message to Congress and accompanying documents, 1849-50, Part III.

³ American Journal of Science, vol. xxxii, 1886, pp. 125 to 138; also in Transactions St. Louis Academy of Science, my report, p. 760.



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township 56, range 33, gave 43.3 degrees, one of the very best observations—that is, not less than 42.6 degrees Fahrenheit surface temperature. These variations are but such as might be expected in the mean soil temperature from streaks of warm years and cold years, as we see from the table of temperature below, from the State Weather Service. In addition to these variations, we have inaccuracies in thermometers, and in my case at least the thermometer was a pocket one, too small to read fractions of a degree accurately. There is also allowance to be made for mine ventilation, tending to increase readings below 60 degrees and decrease those above 70 degrees. There is also the fact that in no case was the real mean depth below the topographic surface computed nor the effect of underground circulation allowed for. All these factors must be allowed for if closer results are to be obtained, though they hardly will change the results 5 per cent.

While State Geologist, I made various observations in 1901, 1906, and 1910, assembled in my report on the Keweenaw series, and a very important set was made by S. Smillie, engineer of Quincy Mine. All observations were assembled in my report in 1911, and all the more important were reprinted by N. H. Darton in United States Geological Survey Bulletin 701. C. E. Van Orstrand is continuing that work.

There is also a method of attacking the problem of mean soil temperature from the Weather Bureau side, thus: Find the mean temperature for a term of years, preferably just preceding the observation. Then assume that for the months when the mean temperature is below freezing, the ground temperature is freezing, for it is known that frost does not go down into the ground more than for a couple of feet. If we also assume that for the first month in spring, when the temperature averages above freezing (April), the ground temperature averages about freezing by the melting snow, we come to 43.7 degrees—a temperature within a degree of the temperatures directly measured.

SUMMARY OF DATA

The data have been so summarized in my report in 1911, and especially in Darton's valuable Bulletin on the Geothermal data of the United States,⁴ that it seems hardly needful to do more than give a few important figures to save the bother of reference and add a few observations I recently made, especially as I understand C. E. Van Orstrand has a yet more elaborate report in hand, which may precede this, and it is to be hoped will include in full the valuable records of the Calumet and Hecla Mine for Alexander Agassiz.

⁴ U. S. Geol. Survey Bulletin 701.

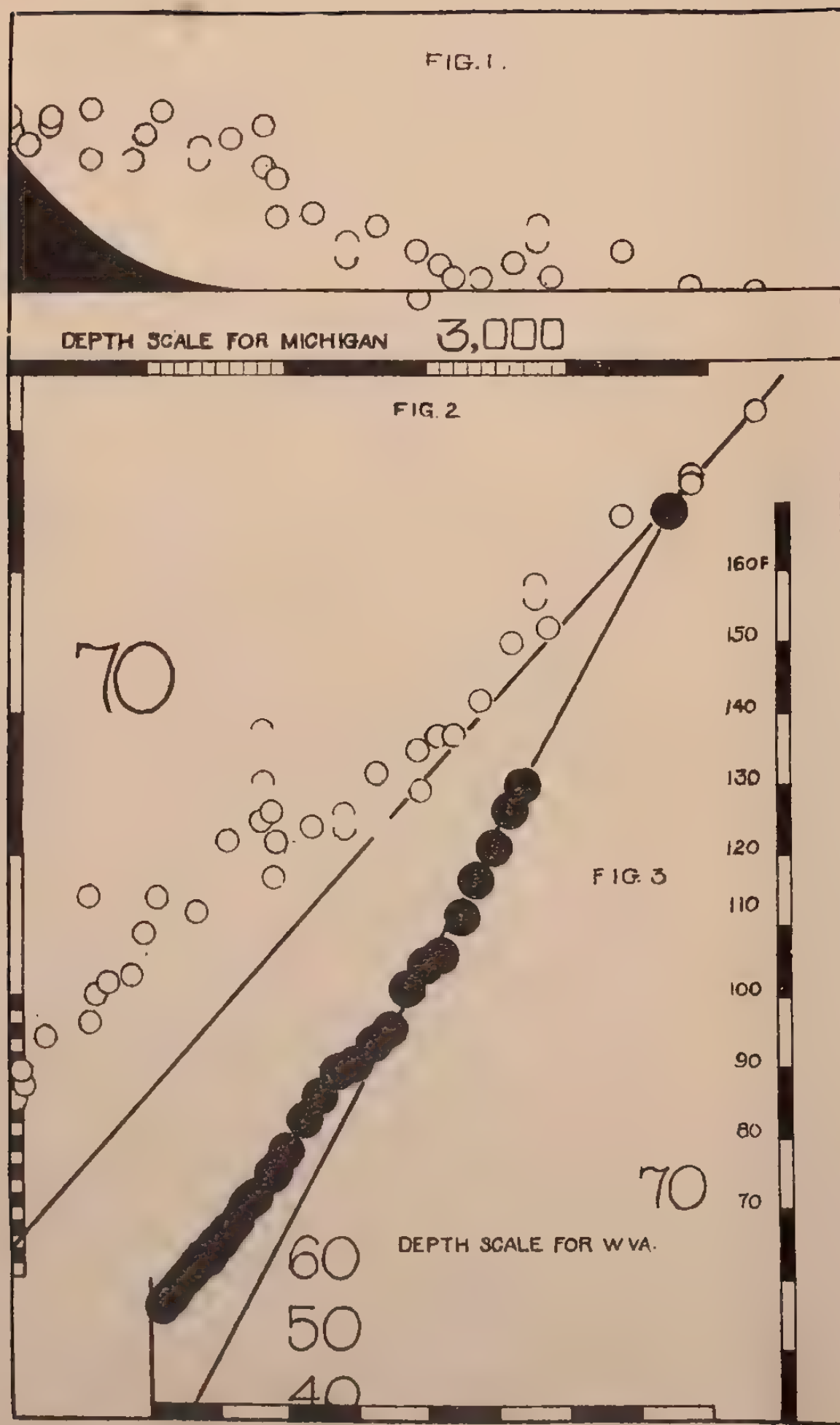


FIGURE 1.—Differences from deepest Gradient in Michigan

Probability curve in left corner.

Figure 1 shows by the heavy black area in the lower left corner the probability curve ($1 - P_m$), unity for m being indicated by a distance. The same distance from left to right as the depth of 1,000 feet, and in ordinates 10 degrees Fahrenheit, and the circles indicate the number of degrees by which the actual rock temperatures observed at depths corresponding to the abscissas are in excess of those which might be expected from the temperatures and the gradient at the bottom of the mine.

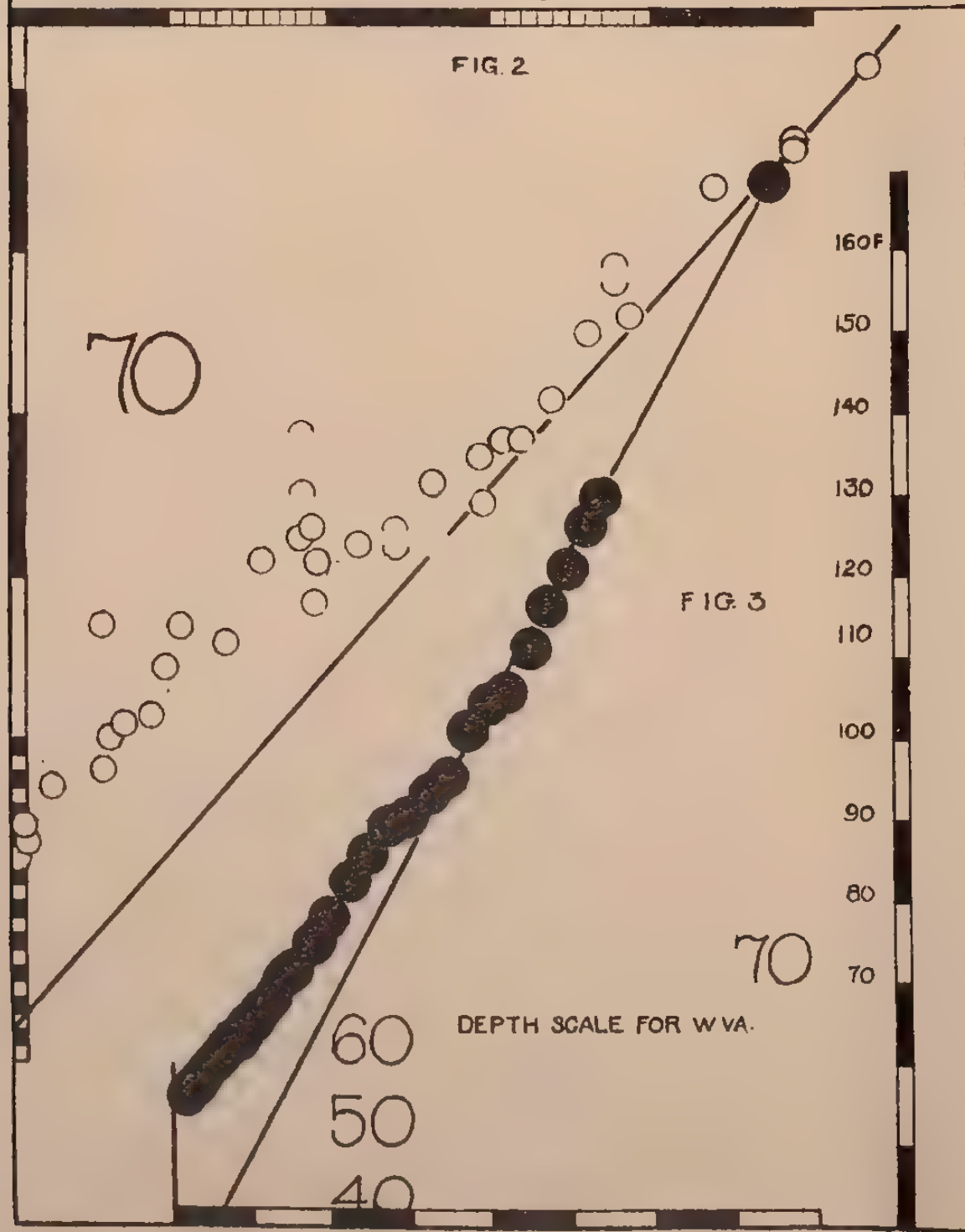


FIGURE 2.—Temperatures in Michigan

Figure 2 shows to the same depth scale, running from left to right, the temperatures (referred to the scale on the left) for various depths in Michigan copper mines, by hollow circles with a radius equivalent to one degree. Half circles indicate a greater range of probable temperature. The heavy black line indicates the bottom gradient, one degree Fahrenheit in 90 feet.

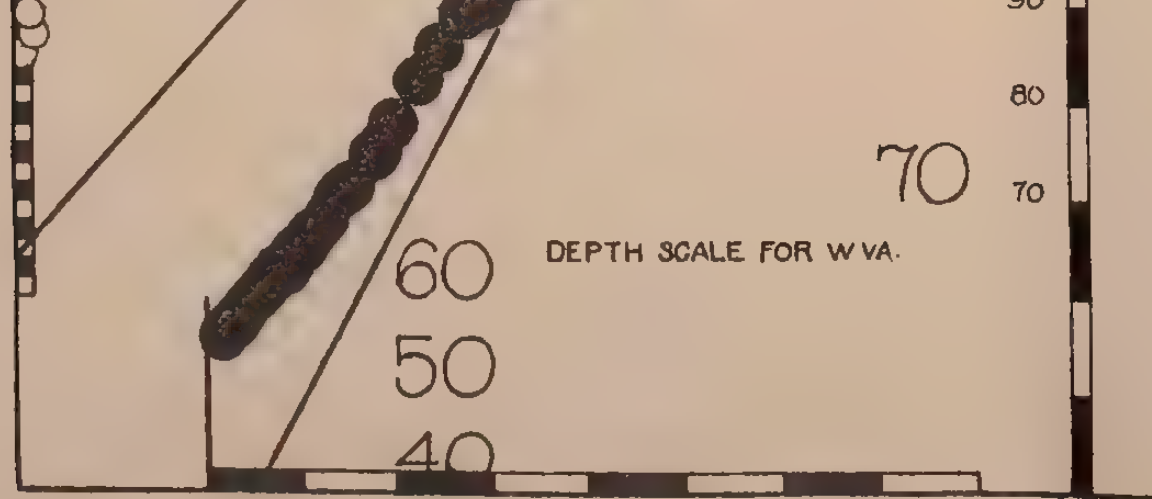


FIGURE 3.—Temperatures in Lake Well, West Virginia

Figure 3 shows by solid black circles with a temperature scale to the right and a depth scale below, with the units in each half the size of those in Figure 2, so that the slopes are directly comparable, the temperatures and the bottom gradient as measured by C. E. Van Orstrand at Lake, West Virginia.

	Degrees Fahrenheit
The hottest and deepest reading was in the bottom of the Tamarack, at (5,367) ⁵ feet.....	91.4
A more reliable record is by C. E. Van Orstrand, on the 81st level of the Calumet and Hecla (checked by myself in August, 1922, as 86 degrees centigrade), at 4,900 feet.....	86.4
I also found at the 78th level (about 4,700 feet from surface).....	84
at the 74th level, about 4,480 feet.....	82
at the 22d level, Ahmeek (1,870 feet), short drill-hole....	65.4
level, Ahmeek, dirt on floor.....	62.3
Isle Royale No. 5 shaft, 21st level (2,664 feet) .....about	66
19th level (2,425 feet).....	63
Champion No. 4 shaft, 8th level.....	51
17th level warmed by mine circulation, probably, compare—	54
Observation in 1909 on the 13th level, when the mine was newer	52.1
Arcadian Consolidated (New Baltic shaft), 1,100-foot level—that is, about (900 feet down).....	58

The more reliable⁶ observations are, however—

Tamarack 5 (4,662) feet.....	82
Quincy (3,875 feet)± (S. Smillie).....	76
(3,856 feet).....	74
(3,246 feet).....	69
(1,130 feet).....	52

C. J. McKie reports the temperature of water flowing from a drill-hole in the Baltic Mine of the Copper Range Company, 36th level (3,277 feet), 71 degrees. On the 3,950-foot level, 1,200 feet from the shaft, rock and air temperature (3,599 feet), 74 degrees. J. W. Alt, chief engineer of the Montreal Mine, Hurley, Wisconsin, reports the temperature of a drift at the bottom of that mine (1,676 feet down) as 19 degrees to 19½ degrees centigrade, and of water flowing from a drill-hole, 70 gallons a minute, as also 19½ degrees centigrade, equal to 67 degrees Fahrenheit.

The following table, for which we have to thank the Bureau of Mines and Mr. T. Dengler, the agent of the Mohawk Mine, shows not only the temperature at various depths, but by the dates, which may also be useful hereafter, something of the error to be expected in observations owing to ventilation, circulation, and variation of temperature in the air between winter (February) and summer (August). The dip of the mine varies

⁵ Numbers in parentheses are vertical depths from the surface, supposed to be flat.

⁶ The depths given by the engineer are below Lake Superior. To this Darton adds 500 feet and I here 550, and I have changed my views as to the more reliable observations. Crosscuts are better sometimes than short drill-holes, farther from ventilation, less affected by boring.

from 36 to 38 degrees, so that the depths from the surface, which varies not over 100 feet, are about 6/10ths (0.6) of the depth down the shaft.

It will be noted that the air at the bottom varies not over 3 degrees Fahrenheit from the rock and water temperature, even when there is a wide range in the surface temperatures, and that it is practically saturated, even when much warmer than the air outside, showing the evaporation that goes on and makes the mine dry and even dusty, although there is moisture in the rock. The bottom temperature of 56 degrees at something like 1,400 feet vertical depth beneath the surface is what might be expected.

Temperature and Draft Comparisons

No.	Date.	Location in mine.	Barometric pressure.	Temperature of mine air.			Remarks.
				Wet bulb. °F.	Dry bulb. °F.	Humid. Per cent.	
1	1/8 to 3/22	Surface, No. 1 upcast shaft.....	29.55	24	24	100	
2	8/23	Fifty feet below collar.....	29.80	55	59	79	Clear sunshine.
3	3/22	No. 1 upcast shaft.....	29.70	50	50	100	
3	2/2	2,200-foot level, No. 1 shaft.....	29.80	50	51	93	
2/2	2/2	2,200-foot level, south drift.....	.....	..	..	...	Rock temperature, 52° F.
8/22	2/2	2,300-foot level, south drift.....	.....	53	53	100	Water temperature, 52° F.
8/22	8/22	Distance to surface on incline, 2,437 feet. Raise connection between 2,300 and 2,400-foot level south.....	30.45	55	56	94	Rock temperature, 56° F.
4	2/3	900 feet south, No. 4, shaft.....	Not taken	56	58	89	
8/22	2/3 to 3/24	Surface to 2,300-foot level on incline 2,243 feet Surface vertical (1,314 feet).....	30.44	55	56	94	
5	3/24	Collar, No. 4 shaft.....	.....	..	..	...	The mean surface level is probably higher by not over 40 feet difference.
8/22	2/3 to 3/24	Strong downcast	28.46	30	30	100	
2/3 to 3/24	Surface, No. 4 shaft.....	29.01	56	61	73	89	
8/22	2/10 to 3/2	Surface, No. 6 shaft.....	28.55	30	31	89	
8/23	2/10 to 3/2	Surface, No. 6 shaft.....	29.01	62	72	57	
8/23	2/10 to 3/2	Surface, No. 6 shaft.....	28.77	34	35	91	
8/23	2/10 to 3/2	Surface, No. 6 shaft.....	29.01	62	66	70	
8/23	2/10 to 3/2	Surface, No. 6 shaft.....	28.78	35	36	91	
8/23	2/10 to 3/2	Surface, No. 6 shaft.....	28.99	60	63	84	
8/23	2/10 to 3/2	Surface, No. 6 shaft.....	29.54	50	50	100	Rock temperature, 51° F.
8/23	2/10 to 3/2	Surface, No. 6 shaft.....	29.96	50	52	87	Water temperature, 50° F.
8/23	2/10 to 3/2	Surface, No. 6 shaft.....	29.45	48	48	100	Rock temperature, 52° F.
8/23	2/10 to 3/2	Surface, No. 6 shaft.....	29.86	52	52	100	Water temperature, 51° F.
10	3/2	1,500-foot level station.....	29.86	50	50	100	
8/23	3/2	No. 6 shaft.....	29.35	50	50	100	
8/23	3/2	Depth on incline, 1,250 feet. Depth on vertical, 804 feet.	29.86	50	51	93	
11	3/25	1,500-foot level, north drift.....	Not taken	50	50	100	
8/23	3/25	700 feet south, No. 5 shaft.....	29.86	50	50	100	
8/23	3/25	1,500-foot level station.....	29.86	50	50	100	
12	3/24	No. 5 shaft.....	29.86	48	49	94	
8/23	3/24	Collar, No. 5 shaft.....	28.50	29	29	100	
13	2/3 to 3/25	Strong downcast	28.95	62	66	80	

The following table from the United States Department of Agriculture, Weather Bureau, at Lansing, shows the average air surface temperatures:

Mean Temperature Data, Calumet, Michigan													
Stations	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1907.....	11.2	12.0	24.6	28.0	38.8	61.6	64.0	61.6	52.6	42.4	30.3	22.4	37.6
1908.....	19.0	15.8	22.1	37.8	49.6	61.0	65.0	63.0	62.7	48.2	33.5	19.8	41.5
1909.....	15.4	14.4	24.3	31.8	46.6	61.0	64.0	65.4	55.0	43.2	35.6	20.0	39.7
1910.....	17.4	12.0	35.4	41.4	46.3	64.2	66.2	62.8	55.2	47.4	26.7	18.0	41.1
1911.....	12.9	20.4	27.2	38.8	53.8	61.2	64.4	61.4	52.8	43.2	26.0	24.5	40.6
1912.....	-1.2	8.2	17.0	36.2	48.4	57.9	63.4	56.6	55.7	47.2	32.6	21.6	37.0
1913.....	14.4	8.8	18.4	40.0	46.4	62.0	60.7	62.7	54.0	42.6	35.3	27.7	39.4
1914.....	18.5	7.8	22.2	33.6	53.8	59.2	66.4	62.4	56.6	54.3	30.3	15.8	39.7
1915.....	13.5	22.3	24.0	45.6	46.4	54.2	60.2	60.6	56.2	44.8	32.8	22.4	40.2
1916.....	14.0	10.0	17.5	35.5	47.5	54.0	70.4	65.2	53.4	43.0	29.4	15.6	38.0
1917.....	10.0	2.4	22.6	32.2	45.4	53.8	65.0	59.3	53.8	35.2	32.6	11.2	35.3
1918.....	5.8	9.5	29.0	37.6	48.8	56.6	61.9	62.7	48.6	45.2	34.9	25.0	38.8
1919.....	21.8	21.0	25.7	37.4	51.8	64.0	67.0	64.2	56.2	40.6	27.2	11.8	40.7
1920.....	6.0	12.4	24.8	31.6	51.8	59.8	62.3	63.3	60.2	52.4	30.4	22.6	39.8
1921.....	20.0	20.8	25.2	44.4	52.4	66.4	71.9	63.9	59.2	45.7	25.6	19.4	42.9
1922.....	13.4	13.8	27.7	37.4	58.7	61.6	62.4	62.5	58.1	....	....	....	....
Mean for 34 years	14.3	13.0	23.0	37.2	48.3	59.4	64.3	62.2	55.4	44.1	30.8	20.6	39.4

If we replace the mean temperatures for December, January, February, March, and April by 32 degrees, because the frost rarely goes more than 2 feet into the ground, often less, we obtain a mean for the ground temperature of 34 years of 43.7 degrees. The lack of snow cover the last of April may nearly balance the snow that may come in November.

LAKE SUPERIOR NOT EFFICIENT

In his work in 1886, the first that brought into relief the low gradient of the copper mines of Michigan as compared, for instance, with those in Montana (the North Butte Mine at Butte, Montana, has at 2,800 feet a rock temperature of 107 degrees Fahrenheit), Wheeler suggested that the low gradient might be due to the cooling effect of Lake Superior.

Unfortunately, this suggestion was taken up by Koenigsberger, the great European and world writer on this subject, in his paper before the International Mexican Congress.⁷ When he speaks of a "small" gradient, he means thereby one in which are few feet needed to obtain 1 degree rise, 9 degrees Fahrenheit = 5 degrees centigrade, 1 degree Fahrenheit for n feet = 1 degree centigrade for 0.55 meters. Thus no change in temperature at all would be a "large" gradient! He says (page 12) that the geothermal gradient is "greatest" near the surface, which agrees with what should be the case if the mean surface temperature has risen since the Ice Age. On the other hand, "the more recent the eruption, the smaller the geothermic gradient." This is altogether in harmony with the contrast between the temperature of the copper mines of Butte, Montana, where the igneous activity is Mesozoic, and those here cited, where the igneous activity is probably before the Taconic uplift and pre-Ordovician. Thus Wheeler's suggestion is spread through the literature. It can not be too strongly emphasized that Lake Superior has nothing to do with the gradient.

In the first place, it will be noticed from the table above that the mean annual temperature of Calumet is only a degree or so from that of the bottom of Lake Superior, which is that of the maximum density of water (38.8 degrees Fahrenheit), a mere trifle compared with the differences in temperature that would exist had Michigan the same gradient as Montana.

In the second place, Lake Superior is 5 miles away, and the lateral effect of cooling on a point only one mile down, common sense would indicate could be but slight, even if B. O. Peirce had not figured it out with a thorough use of mathematics in volumes 34 to 38 of the Proceedings of the American Academy of Sciences.⁸

In the third place, the gradient in the Freda well, down on the edge of Lake Superior, is higher than in the deep mines back from the shore.

⁷ Also Transactions Institution of Mining Engineers, vol. xxxix, part 4, New Castle-upon-Tyne, England, p. 11 of excerpt.

⁸ Vol. 34, pp. 22-25; see also vol. 36, pp. 1-16; vol. 38, pp. 651-660, or Williamson and Adams, Physical Review, n. s., vol. xiv. 1919, pp. 101, 103.

The water rose in an artesian flow from a depth somewhere between 709 and 950 feet at a temperature of about 55 degrees, and the gradient is not far from one degree in 70 feet. It certainly can not be any lower than one degree in 84 feet, as given by Darton.

EFFECT OF LAST ICE AGE

If Lake Superior has no cooling influence, what is the cause of the low gradient? It may be that this is the normal gradient, due to the flow of internal heat from far below. Such a gradient would give a temperature of 1,500 degrees centigrade in 73.5 kilometer, or 2,000 degrees centigrade in 98 kilometer depths, from which lavas might be supposed to come. Then others generally found would be abnormal and affected by chemical reactions, and this is certainly often the case. But one thing that clearly appears from the data should be considered, and that is that the rate of increase is more rapid at the bottom. This, to which we shall return, might be laid to approaching a source of heat below, for in that case the curve of heat would be steeper as we go down, for not only is the heat increasing, but the rate of increase of heat increases as we approach the source of heat. This would imply a continued acceleration of the increase of heat with deeper mining. But in that case we should expect an abnormally high gradient at the bottom, which is not true. The Montana mines reach a greater temperature in half the depth—for example, the North Butte Mine has at 2,800 feet a temperature of 107 degrees Fahrenheit, and the igneous activity there has been much more recent.

The same effect, however, would be produced if the surface temperature had grown milder in later years. It would be the same kind of effect as the progress of a summer wave of heat downward, which has been studied⁹ by Callendar and McLeod and many authorities of weather bureaus and agricultural stations.

That there has been such an effect is certain, for we know that not so many thousands of years ago there was a time when the ice covered this region. There are, indeed, kettle-holes and other signs of melting ice blocks right over the Tamarack and Calumet and Hecla mines. Then we know that this was succeeded by a lake—Lake Duluth—which Leverett has studied,¹⁰ and that probably relatively soon thereafter the land emerged. What the changes were thereafter in ground temperature

⁹ Transactions Royal Society of Canada, vol. i, 1895, sec. 3, fig. 6; see also vol. ii, p. 109, and vol. iii, p. 31.

¹⁰ Michigan Academy of Sciences, 1917.

we do not so well know, but there are some who speak of a relatively mild postglacial climate, which the underground temperatures indicate, as we shall see.

If, then, we assume that when the ice had melted, the temperature rose rather suddenly to the temperature of the bottom of Lake Superior (the temperature of the maximum density of water), and that Lake Duluth was like Lake Superior in that respect, we shall make a reasonable assumption. Yet it is possible that the ice which once filled the kettle-holes may have taken a hundred years after the recession of the ice-sheet to melt. If we assume that since the land emerged above Lake Duluth the mean temperature did not drop, but remained somewhere between the temperature of the maximum density of water (38 degrees Fahrenheit) and the present temperature or higher, but not lower, we make also a probable assumption. There was no readvance of the ice-sheet front, so far as I learn, after the abolition of Lake Duluth.

Now the flow of heat waves into the ground has been a subject of investigation many times,¹¹ and if we can give definite values for the variation of surface temperature, we can calculate the underground temperatures. This we can not do exactly, but we can derive an approximation which will answer present purposes and can be handled by any geologist so as to adapt it to various data without undue labor in getting approximate results, which will be as accurate as present facts warrant.

Suppose that the Ice Age lasted long enough so that the temperature gradient was for great depth and below the depths of observation adjusted to the surface temperature of freezing (32 degrees Fahrenheit under the ice-sheet), and that at the end the temperature rose to 42 degrees and stayed there. This rise would make an addition to the previous temperatures in the shape of a logarithmic curve of the probability integral. It is the curve figured in figure 1. The maximum ordinate is determined by the rise in temperature. In the case chosen this is 10 degrees.

If one wishes to apply it to some other change in surface temperature, one increases the ordinates, or, what is the same thing, changes the unit of the scale of ordinates in proportion.

The ratio of the increase of temperature for various depths is given by the other ordinates to the surface increase.

The depths are connected with the abscissas in this way, that the abscissas are proportional to m where $m = x/2a\sqrt{t}$,—that is, to the

¹¹ See references in my report for 1903, p. 205; also Ingersoll and Zobel, *Mathematical theory of heat conduction*, chap. vii; also E. D. Williamson and L. H. Adams, *Physical Review*, n. s., vol. xiv, August, 1919, p. 100.

depth—and inversely proportional to the square root of the time, and also to the square root of the diffusivity (a^2) = 203 in foot-year units.

One important thing must be noted. If the temperature has risen or fluctuated in any way since the time when the original increase is supposed, but always kept above the assumed initial sudden change, the temperature will always be above the temperatures which we thus compute.

Now we find that the rate of increase or temperature at (figure 2) the bottom of the mines is almost precisely the same as the rate of increase which we get by connecting, for instance, Van Orstrand's observation (probably the most accurate we have) with a surface temperature of 32 degrees. The gradient from Van Orstrand's temperature of 86.4 degrees at 4,900 feet to 32 degrees is 1 degree in 90 feet. Strictly, the depth should be taken from the topographic mean depth, giving more weight to the material immediately overhead; but that would probably not mean a difference in depth of over 100 feet, and the ventilation error is probably as important, but more uncertain.

According to Chamberlin, the gradient of 1 degree in 103 feet from the surface increased to 1 degree in 93.4 feet from 3,324 to 4,837 feet, which will make the bottom gradient just about 1 degree in 90 feet. Figure 2 shows this line and observations of all sorts compiled, and one may tell by inspection how far the statement is true.

We then have this problem: To adjust the curve given by the black area of figure 2 to the excesses of temperature above the line showing the bottom gradient in figure 1 and see how large we can make the scale of abscissas.

After a good deal of study to describe a method which will obtain time estimates with reasonable rapidity and with an accuracy as great as the data at present warrant, I suggest the following: Plot the observations with the temperatures as one set of ordinates and the depths as the other, as they are in figures 2 and 3. Draw a line from a point representing the temperature at the bottom, whose slope shall represent the rate of change of temperature there per unit of depth. In figure 2 its slope is 1 degree in 90 feet. Such a line should pass near or close to the actual temperatures below 3,500 feet. Then plot to the same scale of feet the amounts by which the observed temperatures at the various depths exceed those given by the line just drawn, for the same depth. This has been done in figure 1. It is clear that up to a depth of about 3,000 feet the observations do not systematically exceed the temperatures given by the line drawn. It is also clear that this line hits the surface at a temperature not far from that of freezing.

Then plot from the same origin a curve which is the reverse of the probability curve—that is, through the following points:¹²

$m = x =$	.000	.08	.18	.36	.78	1.00	1.10	1.20	1.40	1.54	1.64	1.84
$y = 1$		.91	.80	.61	.27	.157	.12	.08	.05	.03	.02	.01

These values of y represent the effect of a sudden increase of temperature at a time past (t) and at a depth such that if a^2 is the diffusivity ($= 203$ here, 400 (Kelvin) for units of foot and year) the abscissa $m = (\text{depth } y)/2a\sqrt{t}$.

Now expand this probability curve reversed up, if necessary, by increasing every ordinate in the same proportion so that it shall be close to the surface temperature observations at the surface. Then see how much we can stretch it to the right, increasing all the abscissas in temperatures the same ratio, and still have the observed excess lie above the curve. If we let $m = 1$ correspond to 4,000 feet, most of the observations will lie below the curve in figure 1, and if $m = 1$ corresponds to 2,000 feet, the curve lies way under the observations. The nearest fit is by letting $m = 1$ correspond to 3,000 feet and stretching the curve to the right about three times. Whence, using 203 for the diffusivity instead of Lord Kelvin's 400, as it agrees better with B. O. Peirce's tests on these very rocks, we have $1 = 3,000/(2 \times 14.4 \times \sqrt{t})$. Whence we have $t = 11,080$ years since the rise started to spread downward. This checks well enough with recent estimates by de Geer and Antevis.

It is clear that any other diffusivities or depths at which postglacial changes of climate are not yet perceptible can be readily placed in the above simple equation, which may be expressed in words as follows:

The depth at which the excess of temperature, above that given by the gradient derived from temperatures too deep to be affected by postglacial warming for the said depth, is but 15.7 per cent of the excess of the surface temperature, is twice the square root of the diffusivity multiplied by the time since the sudden postglacial amelioration.

Lord Kelvin took the diffusivity a^2 as $= 400$. Other figures are given in Ingersoll and Zobel's Appendix A, but they omit B. O. Peirce's figures on the copper-bearing rocks,¹³ to wit:

¹² Davis, Brenke, and Hedrick's Calculus Tables, p. 54; Johnson's Theory of Error, and Ingersoll and Zobel, "Theory of Heat Conduction," p. 144.

¹³ Proceedings of the American Academy of Arts and Sciences, May, 1903, vol. xxxviii, no. 23, pp. 658 and 659.

The diffusivities in *c. g. s.* units, used by B. O. Peirce, Callendar and McLeod, Ingersoll and Zobel, and physicists generally, must be multiplied by 33,800 to put them into the foot-year units used by Lord Kelvin, and by 3,153.6 to turn them into meter-year units. There is a decimal point wrong in the figures for meters on page 199 of my report for 1903.

Trap, density.....	2.90	Conductivity	.0031
“	2.82		.0036
Amygdaloid	2.67		.0035
“	2.71		.0034
Conglomerate	2.55		.0047
	2.64		.0052

The diffusivity is the conductivity divided by the density $\times$ the specific heat capacity per unit weight. This latter is not far from .2, but has not been determined. With due regard to the fact that the formation is mainly trap and but very little amygdaloid, and still less conglomerate, I have taken .006 as a fair value for the diffusivity in *c. g. s.* units = 203 in terms of feet and years.

This value is much that which Lord Kelvin found for damp Calton Hill trap, and .0064 in *c. g. s.* units is quoted as an average for certain crustal rocks by Ingersoll and Zobel. It is only about half the value, 400, so often used. It is clear that it would be wrong to assume an inflection of the curve at 4,000 feet, so that there must have been a marked amelioration of the climate since 19,600 years ago. On the other hand, if the heat wave had only gone 2,000 feet, the change would have started only 5,000 years ago. It has plainly gone farther. It looks as though there had been an era of milder climate between the present and the Ice Age, with a mean annual temperature perhaps as much as 60 degrees Fahrenheit.

MATHEMATICAL DISCUSSION

For shallow depths relative to the curvature of the earth the latter may be neglected, and the case may be considered one of the flow of heat in an infinite body with the temperature at different depths at the beginning given, and also the variation of temperature from time to time at the surface. This problem has been treated by many authors beside myself.¹⁴

Among those more readily accessible than my old text-book, Riemann's "Differential gleichungen," the works of W. E. Byerly¹⁵ and Ingersoll and Zobel,¹⁶ the article by Byerly in Merriman's Course in Higher Mathematics may be mentioned, as well as an article by Dr. T. Tamura in the Monthly Weather Review for July, 1903.

It is the case stated in problem 3, on page 88 of Byerly's work, easily solved by combining the solutions of sections 50 and 51.

¹⁴ In vol. vi, the annual report for 1903, and publication of the new series of the publications of the Geological Survey of Michigan, Lansing, Michigan.

¹⁵ "Fourier's series and spherical harmonics," articles 49-54, Ginn.

¹⁶ An introduction to the mathematical theory of heat conduction with engineering and geological applications, Ginn, 1913.

Let $u_{(xt)}$ be the temperature at a depth of (x) at a time represented by (t) , and let

$$(1) \quad u_{(xt)} = u'_{(xt)} + u''_{(xt)}, \text{ where}$$

(2) $u'_{(xt)}$ is such that $u'_{(xo)} = 0$, and $u'_{(ot)} = F(t)$ —that is, is a function of the time only, at the surface, where x is 0.

Also:

$$(3) \quad u''_{(xt)} \text{ is such that } u''_{(ot)} = 0, \text{ and } u''_{(xo)} = f(x).$$

(4) Then $u_{(xt)}$ will be $= F(t)$ at the surface—that is,

$$u_{(ot)} = F(t).$$

(5) Also

$$u_{(xo)} = f(x).$$

But u must also satisfy the differential equation

$$(6) \quad D_t u = a^2 D_x^2 u.$$

A value of $u''_{(xt)}$ is found in Article 50 of Byerly and of $u'_{(xt)}$ that will satisfy this equation (6) as well as the conditions above (by Byerly equations (6) and (7) of page 84, and (10) of page 88. Compare Ingersoll and Zöbel, page 70, equation (22),) and we have:

$$(7) \quad u_{(xt)} = \frac{2}{\sqrt{\pi}} \int_0^\infty x / 2a\sqrt{t} \epsilon^{-\beta^2} F(t - x^2/4a^2\beta^2) \cdot d\beta \\ + \frac{1}{2a\sqrt{\pi t}} \left(\int_0^\infty \left(\epsilon^{-\frac{(\lambda-x)^2/4a^2t}} - \epsilon^{-\frac{(\lambda+x)^2/4a^2t}} \right) \cdot f(\lambda) d\lambda \right)$$

and if we replace the second part by the value given in Byerly's equation (7), page 84 and also write

(8) $m = x/2a\sqrt{t}$, we have:

$$(9) \quad u_{(xt)} = \frac{2}{\sqrt{\pi}} \int_m^\infty \epsilon^{-\beta^2} \cdot F(t - m^2t/\beta^2) d\beta + \frac{1}{\sqrt{\pi}} \int_{-m}^\infty \epsilon^{-\beta^2} \cdot f(x + m\beta/x) d\beta \\ - \int_m^\infty \epsilon^{-\beta^2} f(-x + m\beta/x) d\beta.$$

If the functions F and f are known, these expressions may be expanded into strings of probability integrals of the form

$$P_m = \frac{2}{\sqrt{\pi}} \int_0^m \epsilon^{-m^2} dm.$$

Suppose, for illustration,

$$(10) \quad f(x) = u''_{(xo)} = u_{(xo)} = A + Bx,$$

where we may assume that under the ice-sheet A was about 32 degrees

Fahrenheit and B was $1/90$, then the last part of equation (9) becomes

$$(11) \quad u'' = \frac{1}{\sqrt{\pi}} \int_{-m}^{\infty} \epsilon^{-\beta^2} \cdot \left(A + B(x + m\beta/x) \right) d\beta \\ - \int_m^{\infty} \epsilon^{-\beta^2} \left(A + B(-x + m\beta/x) \right) d\beta.$$

We see that the A terms are equivalent to one-half of $P_{\infty} - P_m - (P_{\infty} - P_m)$.

The B terms, taking out B , m , and x from under the integral sign, are

$$\frac{1}{\sqrt{\pi}} x \left(P_{\infty} + P_m + P_{\infty} - P_m \right) + \frac{mB\beta}{x\sqrt{\pi}} \left(\int_{-m}^{\infty} - \int_m^{\infty} \right) \left(\epsilon^{-\beta^2} \cdot \beta / d\beta \right).$$

The last two integrals are easily solved and are zero, for we may take β^2 as the variable, and $d\beta^2$ is $2\beta d\beta$, and the limits of integration for β^2 are the same, whether β is m or $-m$.

Also $P_{\infty} = 1$; thus all the Bx terms reduce simply to Bx , and

$$(12) \quad u'' = A - P_m + Bx.$$

If $t=0$ $m=\infty$ and $P_m=1$ and $u''_{(x0)} = A + Bx$, as it should.

If, now, we assume for F its simplest value and assume that

(13) $F(t)$ is simply C , a constant, say the present mean annual temperature of Calumet, (43 degrees) $F(t) = C$, then the first part of equation (9) becomes:

$$(14) \quad u' = C(P_{\infty} - P_m)$$

Combining equations 14 and 12, we have this result, that if $u_{(0t)} = C$ and $u_{(x0)} = A + Bx$

$$(15) \quad \text{then } u_{(xt)} = C' + (A - C)P_m + Bx.$$

It is this formula which we have used to estimate the time since the last Ice Age, but it is only a first approximation. The expression for the rate of increase downward under the ice may, perhaps, be nearly enough covered by the expression $A + Bx$, if the ice ages are reasonably long; but the expression for the surface temperature is surely not uniform. It might naturally be a periodic one with a constant temperature during the times that the region is covered with ice. A simple form on which I have done some numerical work assumes $u=0^\circ$, and starts at the middle of an Ice Age, from $t=0$ to $t=T/4$, then lets $u = \sin \frac{t}{2\pi T}$ up to $3T/4$, and then $=0$ to T , where T is one complete period of climatic fluctuation.

Such a curve might not be very far from representing the real fluctuation of temperature, except that the duration of the ice-cap would vary, growing less toward the margin of the ice-cap and also having

more or less lag after the climatic minimum in extending and after the climatic maximum in retreating.

Such a curve may be represented by a series of sine terms

$$(16) \quad u' = F(t) = -\frac{(\sin 2\pi t/T + 1)}{2} + \frac{1}{\pi} (\text{sum of terms } (-1)^{n/2} \left(\frac{2n}{(n^2-1)} \right)).$$

$\sin 2\pi nt/T$, and if we represent $F(t)$ by any such series of sine terms $\sin (2\pi nt/T + l)$ we can get a general expression for $u' (xt)$ by writing for each term $\epsilon - D (\sin 2\pi nt + l - D)$, where $D = (x/ax\sqrt{\pi/T})$ as above.

The resulting series are, however, not always convergent or only semi-convergent, though they are the more rapidly convergent the greater x and the less t , and I have not carried the mathematical work numerically farther, as we know so little regarding post-glacial climate fluctuations. It may be noted however, that each sine term represents an effect on the temperature which is later, and less, the deeper the point the temperature of which is studied.

If we take a relatively simple assumption, we can get a closer approximation to the actual readings. Assume that there was not merely a sudden jump to a temperature of $C (=43 \text{ degrees})$, but that there is a simple sine variation of temperature added. This will bring in three new constants which we can juggle with, to wit, the amplitude of this variation (K), the period of duration of it (T), and the time at which it is zero (L). It is therefore no wonder if we can, by giving them certain values, get pretty good accord. If we note that the actually observed temperatures are most in excess of those obtained by the equation

(15) $u_{(xt)} = C + (A - C)P_m + Bx = 43 + (32-43)Px/2\sqrt{2.3t} + 1/90x$ for about 1,800 feet depth, where they are about 8 degrees in excess, we can get a good approximation by assuming that the crest of the periodic wave above mentioned is now at that depth, and that it was at the surface when the ice went off. Whence we get

$$(16) \quad 2\pi(11,080)/T - 1800\sqrt{\pi/2.3T} + L = \pi/2$$

$$(17) \quad 2\pi(0)/T = 0\sqrt{\pi/2.3T} + L = \pi/2$$

Eliminating from these equations, we find that this would involve a period T of about 90,000 years.

Then by $\sqrt{}$

$$(18) \quad K\epsilon - 1800\sqrt{\pi/2.3(T=90,000)} = 8 = K\epsilon - 224/\sqrt{T}$$

we find that $K =$ about 17 degrees if this is the value of T .

This would imply an immediately postglacial mean temperature of

about 60 degrees, growing gradually cooler to the present temperature of 43 degrees.

OTHER CAUSES OF LOW GRADIENTS

On page 764 of my report on the Keweenaw Series, above cited, I have listed a number of the factors in making the rate of increase of temperature in the copper mines relatively low, apart from any glacial effect. Presented briefly, they are as follows:

(1) Most mines have been put down where oxidation of pyrite or of coal may have increased the temperature as far down as this action went. Temperatures taken in borings for oil may also have been affected by exothermic reactions. Of such reactions there is very little trace in the copper mines. If the calcium chloride found at the bottom of the mines was derived from a chlorine-containing glass, it would be endothermic.

(2) The greater the diffusivity, the less the gradient. The copper-bearing rocks, however, have not a high diffusivity, but a low one, about half the average for the earth used by Kelvin, about two-fifths that of granite, and about two-thirds that of marble. Thus the low gradient must be attributed to some other cause.

(3) An imbibition of waters from above would, of course, lower the gradient. I believe that this has taken place and is an important factor, but I can not use the low gradient as a very weighty argument for such imbibition, because the low gradient might be accounted for otherwise, as we see.

(4) As I have discussed in some detail, the extrusion of the great thickness of lava flows of the Keweenawan would tend to exhaust the heat beneath and make an extra thick crust, and hence a lower gradient. There are indications of such a thicker crust which may be drawn from gravity observations, and from the theory of isostasy.

(5) Not only that, but Joly in his recent book, "The Birth Time of the World," and Arthur Holmes in his book, "Age of the Earth," and in articles contributed to the Geological Magazine, and others have called attention to the fact that a very substantial part of the geothermal gradient may be due to radioactive heat. So as the traps are much less radioactive than the average rocks, according to some investigations, a thickness of 30,000 feet of trap as against the same amount of granite would go a good way toward accounting for a gradient of one foot in 90 rather than one foot in 60, according to some results. The data are, however, not yet very accordant.¹⁷

¹⁷ For references, see Clarke's data of geochemistry. U. S. Geol. Survey Bull. No. 695, pp. 306-315.

(6) The heat of crushing and orogenic actions may very likely tend to raise the average gradient in other places, but be absent here.

On the whole, I must maintain still that "the low gradient is not inconsistent with endothermic reactions and with downward-working waters. It will probably be a long time before we shall be able to say at all definitely which part of the low gradient must have been due to each factor." This will probably come through comparative studies of the gradients in different districts.

OTHER REGIONS

If, however, the temperatures near the surface are higher than would be inferred from the temperatures at the bottom, and the rate of change there, and the consequent less average gradient for the whole depth, than that at the bottom are due to postglacial warming, they must not be confined to the Copper Country. The phenomena must be widespread, although the amount of warming at the surface and the depth to which the warming has penetrated should naturally vary from place to place.

This is indeed the case. It would take us too far to follow it up in a paper which was started as a study of one phase of the question of copper deposition, especially as we may look for a monograph on the subject by C. E. Van Orstrand, who is doing much more accurate work than any I have done; yet, just for illustration, we have plotted in figure 3 his observations of the temperatures in the Lake well.¹⁸ It should be noted that as the rocks are quite different, and the diffusivity also different, and the well near the very edge of the farthest extension of the ice-sheet, one should not expect the size nor the depth of penetration of the postglacial heat wave to be the same. In each case, however, there is a fairly uniform gradient near the bottom of the well. In each case this gradient points to a surface temperature near freezing. The depth of penetration of the heat wave seems somewhat greater in West Virginia, though not as much as might be expected.

Since reading this paper my attention has been called to similar facts and a similar explanation given by Prof. H. Arctowski, of Lwow (Leopol).¹⁹

The records of the deepest mine in the world, that of Saint Juan del Rey, Brazil (6,726 to 6,426 feet), also show a much more rapid rise toward the bottom.²⁰

¹⁸ Darton's U. S. Geol. Survey Bull. No. 701, p. 94, and the reports of the West Virginia Survey; also a separate pamphlet by I. C. White.

¹⁹ Kosmos, May 2, 1923.

²⁰ Mining and Metallurgy, June, 1923, p. 283.

CAMBRO-ORDOVICIAN SECTION NEAR MOUNT ROBSON,
BRITISH COLUMBIA ¹

BY LANCASTER D. BURLING

(Presented before the Society December 28, 1921)

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¹ Manuscript received by the Secretary of the Society September 9, 1922.

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INTRODUCTION (§ 1)

McEvoy² was the first geologist to describe the succession near Yellowhead Pass, between British Columbia and Alberta, on the line of the Grand Trunk Pacific Railway. He applied McConnell's³ terms, Bow River and Castle Mountain, to the clastic lower and the calcareous upper portions respectively, mapping Mount Robson itself as Castle Mountain.

Walcott has published two papers on the geology.⁴ These papers are extensively referred to in the following pages, but this is the proper place to record my regret at having to present an interpretation of the stratigraphy so widely different from that of Mr. Walcott. It is unfortunate that conclusions so diverse from those that have preceded them should be based on field work so incidental as my own, and I should hesitate to present the results of a few days' reconnaissance in an area where another has done several seasons' work if my evidence were not extensive.

The differences between the two interpretations of the sections involve so many points that the general reader who pays too close attention to the descriptions of formations or individual mountains may become confused. For such there is presented a generalized section giving Walcott's interpretation and my own (§ 2), and three tabular correlation tables: the nomenclature and thickness of the formations (§ 3); the included fossils and the age relationships of the formations (§ 4); and the nomenclature of the mountains and the rocks exposed in each formation (§ 5).

The paper throws new light on the stratigraphy and paleontology of a most interesting section of the lowermost Paleozoic, and its details are essential to the future worker who may wish to use the area as a key for exploratory work in the neighboring regions, because some of the formations, stated by Walcott to be typically exposed in certain mountains, are entirely absent from them (Mounts Mumm and Rearguard, for exam-

² Ann. Rept. Geol. Surv. Canada for 1898, vol. xi, 1901, Part D.

³ Idem for 1886, Part D, 1887, pp. 29D-30D.

⁴ New Lower Cambrian subfauna: Smithsonian Misc. Coll., vol. 57, no. 11, 1913, pp. 309-326, pls. 50-54 (published July 21).

Cambrian formations of the Robson Peak district, British Columbia and Alberta. Canada. Idem, vol. 57, no. 12, 1913, pp. 327-343, pls. 55-59 (published July 24).

ple), and because these mountains are those closest to and most easily climbed from the usual camp, at the foot of Robson Glacier. For this reason the writer feels that he should not postpone publication until the faunas can be worked up.

GENERALIZED SECTION, MOUNT ROBSON REGION (§ 2)

WALCOTT	Feet	BURLING	Feet
ORDOVICIAN :		ORDOVICIAN :	
<i>Robson limestones</i> (§ 23)	3,000	The Robson limestones are not known to be present in the Mount Robson region (§ 23 <i>d</i>), the top of Mount Robson appearing to lie at or very close to the horizon of the Extinguisher fauna instead of 3,000 feet above it.	
Massive and thin-bedded limestones, partly arenaceous and dolomitic.		There is a thin-bedded series of shales and intraformational conglomerates, carrying Ordovician fossils, above the top of the Lynx formation. These are exposed in the Extinguisher and in the summit of Mount Rearguard, where they are cut off by erosion 375 feet above the base. They are unnamed in this paper (§ 23 <i>f</i>).	
Fossils: "Near the base" (from the Extinguisher), "where there is a comingling of Upper Cambrian and Ordovician types" (§ 23 <i>c</i>); "also higher up" (drift blocks in a moraine), "where numerous Lingulæ of Ordovician characteristics occur" (§ 23 <i>b</i>).			
Total Ordovician	3,000	Total Ordovician	375
UPPER CAMBRIAN :		UPPER CAMBRIAN :	
<i>Lynx limestones</i> (§ 24)	2,100	<i>Lynx formation</i> (§ 24)	5,000
Thin-bedded gray and bluish gray limestone with bands of shale.		More or less thin and irregularly bedded series of limestones and shales, marked at the base by ripple-marks, mud-cracks, and casts of salt crystals.	
Fossils: None.		Thickness obtained in Mounts Lynx and Rearguard (§§ 14, 18, 24).	
		Fossils: Abundant and in a score or more horizons.	
Total Upper Cambrian	2,100	Total Upper Cambrian	5,000

	Feet		Feet
MIDDLE CAMBRIAN:		MIDDLE CAMBRIAN:	
<i>Titkana limestones</i> (§ 25)...	2,200	<i>Titkana limestones</i> (§ 25)...	2,550
Massive beds of thin layers of bluish gray limestone with bands of dolomitic limestone.		More or less thin-bedded usually dark-colored limestones with bands of shale and beds of dolomitic limestone.	
Thickness in Mounts Titkana and Rearguard (§ 25a).		Thickness in Titkana Peak (§§ 18, 24d, 25a).	
Fossils: An upper horizon comparable with the Stephen and a lower horizon 1,000 feet below (§ 25a).		Fossils: Abundant and in a score or more of horizons, including the upper one of Walcott, which occurs 600 feet above the base of the formation, and the lower one, which occurs at the base of the formation (§ 25a).	
<i>Mumm limestones</i> (§ 26)....	600	Not present in the section.	
Massive-bedded gray arenaceous limestone.		The formation was described from an exposure of the "Hota" (§§ 30b, 30g, 32c), but was assigned to a position in the section which made it and the Tatei synonymous. The latter name has been accepted for the formation (§ 28b).	
Thickness estimated from an exposure of the "Hota" in Mumm Peak (§§ 26b, 30b).			
Fossils: None.			
<i>Hitka formation</i> (§ 27).....	1,700	Not present in the section.	
Alternating bands of thin layers of arenaceous limestones and shales.		The Hitka and the Titkana are synonymous and the latter term has been accepted (§ 25b).	
Thickness estimated from an exposure of the Titkana in Mount Hitka (§ 27b).			
Fossils: None.			
<i>Tatay limestones</i> (§ 28).....	800	<i>Tatei limestones</i> (§ 28).....	1,000
Massive-bedded gray arenaceous limestone.		More or less massive blue to blue gray limestones, 1,000 feet being exposed beneath Titkana above Lake Adolphus and 900 feet in Tatei cliff, but upper and lower boundaries uncertain, because Walcott's description is general and does not record fossils.	
Thickness obtained in Tatei cliff.		Fossils: Frequent, several lots being secured, but less fossiliferous than underlying Chetang or overlying Titkana.	
Fossils: None.			

	Feet
<i>Chetang limestones</i> (§ 29)...	900
Bluish gray thin-bedded limestones.	
Thickness in Chetang cliff.	
Fossils: An upper horizon and a lower 250 feet below, with <i>Albertella</i> .	
Total Middle Cambrian.....	6,200

Lower-Middle Cambrian boundary Walcott (§ 8a).	
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LOWER CAMBRIAN:

<i>Hota formation</i> (§ 30).....	800
Gray arenaceous limestones and siliceous shales alternating with massive quartzitic sandstones.	

Thickness obtained from an exposure of the "Tah" in Mumm Peak, near Mural glacier, and lithology is descriptive of the "Tah" (§ 30*d*).

Fossils: Walcott (personal communication) states that the "new Lower Cambrian subfauna" with *Olenellus* was referred by error to the Mahto and belongs here (see § 32*d* and note opposite).

<i>Mahto sandstones</i> (§ 31)....	1,800
Massive-bedded quartzitic sandstones with bands of siliceous shale.	

Fossils: None (page 339 of Walcott). (See footnote in § 31*c*.)

	Feet
<i>Chetang limestones</i> (§ 29)...	950
Thin-bedded blue limestones with some shales.	
Thickness in Chetang cliff.	
Fossils: Abundant in many horizons. <i>Albertella</i> was found in Chetang cliff, and in several horizons on Mural Brook, and in the summit of Mumm Peak (§ 29 <i>b</i>).	

<i>Adolphus limestone</i> (§ 30)...	400
Gray arenaceous limestone, changing on the strike, near the base, to thin-bedded blue-black limestones.	

Thickness obtained in Mumm Peak (§§ 30*f*, 30*g*, 32*c*).

Fossils: Well-defined Middle Cambrian fossils were found at two horizons in the thin-bedded limestones at the base of the Adolphus.

The "new Lower Cambrian subfauna" of Walcott does not occur in the Adolphus ("Hota"), but in the "Tah" (see § 32*e*).

Total Middle Cambrian.....	4,900
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Lower-Middle Cambrian boundary, Burling (§ 8).	
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LOWER CAMBRIAN:

<i>Mahto sandstones</i> (§ 31)....	1,200
Comparatively thin-bedded quartzitic sandstones with purplish sandy shales.	

Thickness estimated in Mumm Peak (§ 31*d*).

Fossils: I first placed the "new Lower Cambrian subfauna" with *Olenellus* and *Pædeumias* here (§ 32*d*), but as the boundary is now drawn that fauna belongs with the "Tah." No other fossils found.

	Feet		Feet
<i>Tah formation</i> (§ 32).....	800	<i>Mural limestone formation</i> (§ 32)	1,000
Siliceous shale and interbedded siliceous limestones.		Massive arenaceous limestones with interbedded shales and quartzitic sandstones.	
Thickness in Tah Peak.		Thickness in Mumm Peak.	
Fossils: None.		Fossils: Abundant at many horizons, the "new Lower Cambrian subfauna" occurring 550 feet below top (§ 32e).	
<i>McNaughton sandstones</i>	500	<i>Unnamed sandstones</i> (§ 33)..	400
Thickness in Yellowhead Pass (§ 33).		Thickness in Mumm Peak, base concealed.	
Fossils: None.		Fossils: None.	
<i>Total Lower Cambrian</i>	3,900	<i>Total Lower Cambrian</i>	2,600
<i>Total Cambrian</i>	12,200	<i>Total Cambrian</i>	12,500
<i>PRE-CAMBRIAN:</i>		<i>PRE-CAMBRIAN:</i>	
<i>Miette sandstones</i> (§ 34)....	2,000	Not studied.	

NOMENCLATURE AND THICKNESS OF FORMATIONS (§ 3)

Mr. Walcott described twelve formations in his papers on the Mount Robson region—ten from the region itself, one from the McNaughton Mountains, and one from the Miette River. Because of duplications and changes in the interpretation of the stratigraphy in some of the mountains, it has been necessary to reduce the number of these formations to seven. The changes which have been required are expressed in the following table, in which there are sectional references to the detailed explanations which occur in the text. The formations are listed in stratigraphic order, reading from the top down (Table 1).

INCLUDED FOSSILS AND AGE RELATIONSHIPS OF FORMATIONS (§ 4)

The main differences in the formations and fossil horizons listed by Walcott and the writer are (*a*) the discovery of thin-bedded Ordovician limestones and shales above the Lynx instead of the Robson limestones, and (*b*) the reference of the New Lower Cambrian subfauna, a horizon referred by Walcott to the "Hota," but found by the writer in the "Tah" (Table 2).

NOMENCLATURE OF MOUNTAINS AND ROCKS EXPOSED IN EACH FORMATION (§ 5)

Mr. Walcott has made several changes in or additions to the names applied to the topographic features of the Mount Robson region by the

Formation name (Walcott).*	
Robson limestones (above Extinguisher fauna).	Appal Mo 23d
Lynx limestones (below Extinguisher fauna).	Great 3,00 stra Wa Ex
Titkana limestones.	
Mumm limestones.	Descr an wh phu
Hitka formation.	Merel Tit
Tatay limestones.	Spelli by Boa
Chetang limestones.	
Hota formation.	Confu sils of "Ta "M
Mahto sandstones.	
Tah formation.	Confu sils of "H the
McNaughton sandstones.	Left u son

* Names in stratigraphic order.

TABLE 1

Formation name (Walcott).*	Remarks.	Accepted formation name (Burling).	Estimated thickness (Walcott).	Measured thickness (Burling).
Robson limestones (above Extinguisher fauna).	Apparently absent from Mount Robson region (§§ 23 <i>d</i> and 23 <i>e</i>).	Unnamed (§ 23 <i>f</i>).	3,000 feet in Mount Robson.	375 feet of Ordovician shales and thin-bedded limestones occur above Extinguisher fauna in Mount Rearguard (§ 23 <i>f</i>).
Lynx limestones (below Extinguisher fauna).	Greatly enlarged by finding 3,000 feet of additional strata between the top of Walcott's Lynx and the Extinguisher fauna.	Lynx formation (below Extinguisher fauna).	2,100 feet in "Lynx Mountain" (§ 14).	5,000 feet in the real Mount Lynx and in Mount Rearguard.
Titkana limestones.		Titkana limestone.	2,200 feet in Mount Titkana.	2,500 feet in Mount Titkana.
Mumm limestones.	Described and named from an exposure of the "Hota," which is now called Adolphus (§§ 26 <i>b</i> , 30 <i>b</i> , 32 <i>c</i>).	(Absent.)	600 feet in Mumm Peak.	It does not occur in Mumm Peak (§§ 16 and 32 <i>c</i>).
Hitka formation.	Merely a duplication of the Titkana (§ 25 <i>b</i>).	(Absent.)	1,700 feet in Mount Hitka.	It is the Titkana which occurs in Mount Hitka (§ 27 <i>b</i>).
Tatay limestones.	Spelling changed to Tatei by Canadian Geographic Board (§ 21).	Tatei limestones.	800 feet in Tatay cliff.	1,000 feet in Mount Titkana and Tatei cliff.
Chetang limestones.		Chetang limestones.	900 feet in Chetang cliff.	950 feet in Chetang cliff and in the top of Mumm Peak.
Hota formation.	Confused (stratigraphy, fossils, localities, and mode of occurrence) with the "Tah," the Mahto, and the "Mumm" (§ 30).	Adolphus limestone (§ 30 <i>g</i>).	800 feet in Hota cliff.	400 feet below the Chetang, in the top of Mumm Peak.
Mahto sandstones.		Mahto sandstones.	1,800 feet in Mahto Mountain.	1,200 feet (estimated) in Mumm Peak.
Tah formation.	Confused (stratigraphy, fossils, localities, and mode of occurrence) with the "Hota," the Mahto, and the "Mumm" (§ 32).	Mural limestone (§ 32 <i>g</i>).	800 feet in Tah Mountain.	1,000 feet in Mumm Peak.
McNaughton sandstones.	Left unnamed in Mount Robson region (§ 33 <i>b</i>).	Unnamed (§ 33 <i>b</i>).	500 feet in McNaughton Mountains.	400 feet in Mumm Peak, base not exposed.

* Names in stratigraphic order, youngest at the top.

Formation (Walcott).	
Robson limestones.	Drift and gull (§
Lynx limestones.	None
Titkana limestones.	An ph low
Mumm limestones.	None
Hitka formation.	None
Tatay limestones.	None
Chetang limestones.	An low
Hota formation.	The Ca fav 30
Mahto sandstones.	None
Tah formation.	None
McNaughton sand- stones.	None

TABLE 2

Formation (Walcott).	Fossils (Walcott).	Age (Walcott).	Formation (Burling).	Fossils (Burling).	Age (Burling).
Robson limestones.	Drift fossils (§ 23 <i>b</i>) and the Extin- guisher fauna (§ 23 <i>c</i>).	Ordovician.	Unnamed series, shales and thin- bedded limestones overlying the Lynx (§ 23 <i>f</i>).	4 horizons.	Ordovician.
Lynx limestones.	None.	Upper Cambrian.	Lynx formation.	25 horizons.	Upper Cambrian.
Titkana limestones.	An upper (Ste- phen) and a lower.	Middle Cambrian.	Titkana limestones.	17 horizons above the Stephen, 4 below.	Middle Cambrian.
Mumm limestones.	None.	Middle Cambrian.	Synonym of the Tatei (§ 26 <i>b</i>).	Absent from the section.	Absent from the section.
Hitka formation.	None.	Middle Cambrian.	Synonym of the Titkana (§ 27 <i>b</i>).	Absent from the section.	Absent from the section.
Tatay limestones.	None.	Middle Cambrian.	Tatei limestone (§ 21).	4 horizons.	Middle Cambrian.
Chetang limestones.	An upper and a lower (<i>Albertella</i>).	Middle Cambrian.	Chetang limestone.	8 horizons above the <i>Albertella</i> zone, 3 in it, and 2 below.	Middle Cambrian.
Hota formation.	The "New Lower Cambrian sub- fauna" (§§ 30 <i>c</i> , 30 <i>d</i> , 32 <i>b</i> , 32 <i>c</i>).	Lower Cambrian (§§ 8 <i>a</i> and 30 <i>e</i>).	Adolphus limestone (§ 30 <i>g</i>).	2 horizons, both near the base.	Middle Cambrian.
Mahto sandstones.	None.	Lower Cambrian.	Mahto sandstones.	None.	Lower Cambrian (§§ 8 <i>b</i> , 30 <i>e</i>).
Tah formation.	None.	Lower Cambrian.	Mural limestone (§ 32 <i>g</i>).	4 horizons, includ- ing the horizon of the "New Lower Cambrian subfauna," 750 feet below top (§§ 32 <i>b</i> to 32 <i>e</i>).	Lower Cambrian.
McNaughton sand- stones.	None.	Lower Cambrian.	Unnamed (§ 33 <i>b</i>).	None.	Lower Cambrian.

Usual geographic name.	Walcott ranged in
The Extinguisher.	Billings'
(Unnamed.)	Chetang
(Unnamed.)	Mount E
(Unnamed.)	Hota cli
Mount Rearguard.	Iyatung
(Unnamed.)	"Lynx M
(Unnamed.)	Mahto M
(Unnamed.)	McNaughtains.
Mumm Peak.	Mumm P
Lynx Center.	Phillips in text
Lynx Mountain.	Phillips in lege
Mount Robson.	Robson I
Moose Pass Station.	Tah Mou
(Unnamed.)	Tatay cli
Ptarmigan Peak.	Titkana

TABLE 3

Usual geographic name.	Walcott's name, arranged alphabetically.	Accepted name.	Formations exposed (Walcott), named in order, the youngest first.	Formations exposed (Burling), named in order, the youngest first.
The Extinguisher.	Billings' Butte.	The Extinguisher.	The Extinguisher fauna (§ 23c).	The Extinguisher fauna (§§ 6a, 11, 14, and 23f).
(Unnamed.)	Chetang cliff.	Chetang cliff.	Chetang limestones.	Chetang limestones.
(Unnamed.)	Mount Hitka.		Mumm, Hitka, and Tatay.	Lynx, Titkana, Tatei, and Chetang (§ 12).
(Unnamed.)	Hota cliff.		Hota formation (superseded by Adolphus limestone, (§ 30g).	Upper and lower contacts not shown. These are exposed in Mumm Peak (§§ 13, 16).
Mount Rearguard.	Iyatunga Mountain.	Mount Rearguard.	Titkana.	Extinguisher fauna (at top) underlain by Lynx formation to exposed base (§ 18).
(Unnamed.)	"Lynx Mountain."	Still unnamed (§§ 14 and 17).	Lynx formation (§ 14).	Unknown (see § 14, last paragraph).
(Unnamed.)	Mahto Mountain.	Mahto Mountain.	Mahto sandstones.	Upper and lower contacts with fossiliferous formations shown in Mumm Peak.
(Unnamed.)	McNaughton Mountains.		McNaughton sandstones.	Not visited (§ 33).
Mumm Peak.	Mumm Peak.	Mumm Peak.	Titkana, Mumm (typically), Hitka, Tatay, Chetang, and Hota (§ 16).	Chetang, "Hota" (Adolphus), Mahto, "Tah" (Mural), and unnamed basal sandstones (§§ 30g and 32c).
Lynx Center.	Phillips Mountain in text (§ 17).			
Lynx Mountain.	Phillips Mountain in legend (§ 17).	Lynx Mountain.	Lynx limestones.	Lynx formation in part (§§ 11, 24b, and 24d).
Mount Robson.	Robson Peak.	Mount Robson.	Robson limestone (3,000 feet) forming top, with Extinguisher fauna below (§ 23a).	Probably Lynx formation (5,000 feet), with Extinguisher fauna at or near top (§ 23d).
Moose Pass Station.	Tah Mountain.		Tah formation.	Mural limestone supersedes this (§ 32g).
(Unnamed.)	Tatay cliff.	Tatei cliff.	Tatay limestone.	Tatei limestone (§ 28b).
Ptarmigan Peak.	Titkana Peak.	Titkana Peak.	Titkana and Mumm.	Titkana and Tatei (§ 22).

earlier explorers. For such of these as are concerned in the study of the geology, the following table is prepared. The differences between the formations stated by Walcott as occurring in a mountain and the formations found there are not due to varying interpretations of the same strata, but to the fact that Mr. Walcott did not allow for possible faulting between adjacent mountains in making visual correlations. (Mounts Titkana and Rearguard, for example), or did not allow enough where the faulting is evident (Mounts Hitka and Mumm, for example) (Table 3).

CONTACT BETWEEN THE UPPER CAMBRIAN⁵ AND POST-CAMBRIAN
(ORDOVICIAN OR DEVONIAN) (§ 6)

(§ 6a.) According to Walcott (page 336 of his paper), "there is no known well-defined lithological break between the Ordovician and the Cambrian" in the Mount Robson region. He draws the line tentatively in the isolated series of thin-bedded and shaly limestones exposed in the Extinguisher ("Billings Butte"), "where there is a commingling of the Lower Ordovician and the Upper Cambrian faunas."

This fauna has since been discovered in place in the summit of Mount Rearguard (§§ 18 and 23f), and evidences of disconformity have been observed at the line where the Cambro-Ordovician boundary is now drawn. The break in the section does not appear to be so important as that between the Middle and Upper Cambrian (§ 7), but it should be mentioned that the Ordovician, as here used, appears to include the Ozarkian of Ulrich, and that we have in our fossil collections many fossil horizons from the beds immediately above and below the boundary as we have drawn it.

(§ 6b.) The contact between the Cambrian and the Ordovician seemed so important, and the new light obtained on the problem from widely separated districts of the Cordilleran region by the writer was so extensive, that when the first draft of this paper was written he expected to postpone that general subject to a separate publication. The collections are not now available to him in his peregrinations, but it will be of interest to students to know that the boundary between the Upper Cambrian and the overlying rocks in both the Canadian Pacific Railway section and the Grand Trunk Railway section exhibits certain remarkable features.

(§ 6c.) As was announced in 1916,⁶ there is a large area in which the relations of the Upper Cambrian and early Ordovician to the Devonian are those of angular conformity, and the detection of the line is so difficult that geologists have united into one group the rocks above and below.

⁵ The discussion includes a consideration of the Ozarkian.

⁶ Summary Rept. Geol. Surv. Canada for 1915, p. 98, 1916.

The Devonian has been found to lie disconformably on the Cambrian or early Ordovician rocks in Roche Miette, west of Jasper, Alberta;⁷ in North Kootenay Pass, south of Crowsnest Pass, between British Columbia and Alberta;⁸ near Elko, west of Fernie, British Columbia;⁹ on Beaver Creek, northeast of Helena, Montana;¹⁰ in the Sawback Range west of Banff, Alberta; in the mountains at the east end of Lake Minnewanka, north of Banff, Alberta; in the mountains at the head of Upper Columbia Lake, south of Golden, British Columbia, and elsewhere.

A survey of these various occurrences leads to the following conception of the relations. In the Canadian Pacific Railway section it appears that where the Upper Cambrian is thick and characterized by what we might call the accepted type of Upper Cambrian fauna it passes up into the true Ordovician (Black River, Trenton, and Richmond) without known passage through the Ozarkian fauna, but that where the Upper Cambrian is thin and characterized by an Ozarkian fauna it is overlain directly and without angular unconformity, sometimes even without easily observable disconformity, by the Devonian. The latter condition of affairs is, however, characteristic only of the eastern margin of the Rocky Mountain belt, though it persists along this eastern margin from Roche Miette on the north almost to the International Boundary, a distance of 335 miles.

(§ 6*d*.) In the Mount Robson region, central with respect to the entire Rocky Mountain belt, the Upper Cambrian is fairly thick, but passes upward into rocks carrying faunas comparable with certain phases of the Ozarkian. On the eastern edge of this portion of the Rocky Mountain belt, however, the Upper Cambrian of Roche Miette is thin, carries Ozarkian faunas, and is overlain directly by the Devonian, as it is in the Sawback Range and in the vicinity of Lake Minnewanka, on the Canadian Pacific 200 miles to the south. If the analogy between the two sections (Canadian Pacific and Grand Trunk Pacific) holds and we are right in the generalization which we have made for the Canadian Pacific Railway section, we might expect to find true Ordovician in the fairly central Mount Robson region. The presence of apparently Ozarkian types near Mount Robson, where the rocks are surprisingly fossiliferous, might on the other hand lead us to suppose that our generalization needs certain modifications, and that we may have merely overlooked the Ozarkian faunas in our collecting from the thick but relatively less fos-

⁷ Dowling: Summary Rept. Geol. Surv. Canada for 1911, pp. 205-208, 1912.

⁸ Adams: Discovery of phosphate of lime in the Rocky Mountains (of Canada). Commission of Conservation, Canada, 1915, p. 13.

⁹ Schofield: Summary Rept. Geol. Surv. Canada for 1913, pp. 131-132, 1914.

¹⁰ Walcott: Smithsonian Misc. Coll., vol. 64, 1916, p. 271.

siliferous sections of the Upper Cambrian in the Rocky Mountain geosyncline to the south. But the future student should not be surprised if he finds the Devonian resting on the semi-Ozarkic faunas which immediately overlie the Lynx formation in the Mount Robson region, and this might even happen in the summit of Mount Robson itself.

The problems involved are very interesting, and the rocks may prove even more generous to the student who shall make more than a rapid reconnaissance in this fossiliferous region.

CONTACT BETWEEN THE MIDDLE AND UPPER CAMBRIAN (§ 7)

Walcott draws the line between the Middle and Upper Cambrian at the base of the "unfossiliferous" Lynx limestones and above the Titkana limestones, in which he found a fauna comparable with that of the Stephen formation. The discovery of many other fossil horizons in the 1,600 feet which separate the Stephen faunal horizon of the Titkana from the Lynx, together with abundant fossils in a dozen or more horizons in the Lynx formation, has shown the author the faunal correctness of the separation, and the writer has already described¹¹ the lithological and stratigraphical grounds which confirm the presence at this point in the section of a break similar in character and magnitude to the break between the Middle and Upper Cambrian in the Canadian Pacific Railway section 200 miles to the south. In each section the upper layers of the Middle Cambrian exhibit the downwarping which has been ascribed by the writer to peculiar conditions of subaërial desiccation, and the lower layers of the Upper Cambrian exhibit mud-crack, ripple-mark, cast-of-salt crystal, and other shallow-water sedimentation phenomena.

CONTACT BETWEEN THE LOWER AND MIDDLE CAMBRIAN (§ 8)

(§ 8a.) Walcott places the boundary between the Lower and Middle Cambrian between the "Hota" and the Chetang, the former described as carrying the "new Lower Cambrian subfauna" with *Olenellus*, the latter as carrying *Albertella*.

The lowest fossil horizon secured by Walcott in the Chetang is 550 feet above the base of the formation in Chetang cliff, and evidence is presented, in the discussion of the "Hota," Mahto, and "Tah" formations

¹¹ Shallow-water deposition in the Cambrian of the Canadian Cordillera. Ottawa Nat., vol. 29, 1915, pp. 87-88.

Notes on the stratigraphy of the Rocky Mountains, British Columbia and Alberta. Summary Rept. Geol. Surv. Canada for 1915, p. 99, 1916.

Downwarping along joint planes at the close of the Niagaran and Acadian. Journ. Geol., vol. 25, 1917, pp. 145-149.

(§§ 30*c-d*, 31*a*, 32*b-e*) to show that the "new Lower Cambrian subfauna" with *Olenellus*, referred by Walcott to the "Hota," occurs in the "Tah," nearly 1,750 feet below the base of the Hota, and therefore more than 2,250 feet below *Albertella*. Since we have discovered typical Middle Cambrian fossils in the basal layers of the "Hota" or its immediately underlying calcareous beds, we are free to feel a reasonable doubt as to the presence of *Olenellus* in the "Hota."

(§ 8*b*.) We have, therefore, no alternative but to draw the line between the Lower and the Middle Cambrian below the "Hota." Just where to draw it below the "Hota" is, however, a little more difficult (§§ 30*f*, 31*c*, 32*d-e*), for, curiously enough, the immediately underlying clastic series does not yield *Olenellus* as it does in the Canadian Pacific Railway section. Here—that is, in the Mount Robson region—the first beds resembling the 20-foot bed of limestone which has been described¹² as forming the top of the Lower Cambrian in the Canadian Pacific section are those of a bed approximately 2,000 feet below the base of the "Hota," in the Mumm Peak (north face) section. The highest Lower Cambrian horizon secured by ourselves from the beds underlying the "Hota" is separated from that Middle Cambrian formation by some 1,500 feet of quartzites and arenaceous limestones, and on paleontologic grounds the line between the Lower and the Middle Cambrian merely lies somewhere between. From a stratigraphic standpoint, and in the absence of any evidence of unconformity below, the line appears to be correctly drawn at the top of this quartzite series; and, since the top of the Mahto was also drawn at the top of the quartzitic series, the top of the Lower Cambrian and the top of the Mahto coincide. (See §§ 30 and 31.)

In the Mount Robson region, therefore, an apparently unfossiliferous dominantly quartzitic series approximately 1,500 feet thick separates the highest *Olenellus* fauna from known Middle Cambrian; and, while we have placed these rocks in the Lower Cambrian, it will be worth while to contrast and compare the section with those in other portions of the Cordillera.

(§ 8*c*.) Known Middle Cambrian limestones somewhat abruptly overlie unfossiliferous quartzites in the Stansbury Range, Simpson Range, Beaver River Range (Cricket Spring), and House Range sections of Utah (first group). In the Onaqui Range, Blacksmith Fork Canyon, East Fork Canyon, Geneva, Wasatch Canyon, and Promontory Point sections (second group), however, there appears to be an almost imperceptible gradation between the quartzites and the limestones; and, since the underlying quartzites in a section (Mill Canyon, Idaho) closely re-

¹² Burling: Museum Bull., Geol. Surv. Canada, no. 2, 1914, pp. 106 and 115.

lated to the second group have yielded true Middle Cambrian fossils, the quartzites in the second group of sections have all been tentatively referred to the Middle Cambrian.¹³ The succession in the Mount Robson region is abrupt, however, and more nearly resembles that in the first group of sections named. The underlying quartzites in all the sections of this group have so far proven unfossiliferous; but, since *Olenellus* has been collected from the upper part of the quartzitic series in the closely related southern Wasatch Range (Big Cottonwood) section and in the Oquirrh and Pioche sections, the quartzites in these, as well as those in the first group of sections, and in the Mount Robson region, are referred to the Lower Cambrian.

(§ 8*d*.) In the Canadian Pacific Railway section it has not been so much a question of where to draw the line in an unfossiliferous interval as of where to draw the line in a very fossiliferous series where scattered fragments of *Olenellus* have been identified from horizons well above the basal clastics. Such occurrences have been ascribed by the writer to recurrence, and the discovery of the presence at the top of these clastics of a diastrophic break of considerable magnitude¹⁴ seems to confirm this delineation of the Lower-Middle Cambrian boundary. Walcott does not accept recurrence as an explanation and minimizes the stratigraphic importance of the unconformity at the base of the Mount Whyte, placing¹⁵ the boundary at the top of the Mount Whyte, well above any possible occurrence of *Olenellus*. A recent textbook¹⁶ even makes the statement: "It should be made clear that the genus *Olenellus* became extinct before the Middle Cambrian strata were deposited," and calls it one of the principles laid down as a basis for the subdivision of the Cambrian system. But we are coming to realize that the sudden introduction of new forms is of far more importance than the ultimate extinction of the old, and that in the delimitation of stratigraphic boundaries we must substitute the proper valuation of a debatable series of diastrophic and organic phenomena for a simple yes or no.

(§ 8*e*.) In the Mount Robson region it is more nearly possible to use the shorter method; but even here the drawing of the Lower-Middle Cambrian boundary involves placing it somewhere in an unfossiliferous 1,200-foot quartzite series (Mahto) which separates known Lower Cambrian limestones ("Tah" = Mural) below from known Middle Cambrian limestones ("Hota" = Adolphus) above. We have given our reasons for

¹³ Burling: Museum Bull., Geol. Survey Canada, no. 2, 1914, p. 110.

¹⁴ Summ. Rept. Geol. Surv. Canada for 1915, p. 100, 1916.

¹⁵ Smithsonian Misc. Coll., vol. 67, no. 3, 1917, pp. 61-67.

¹⁶ Miller: Historical Geology, 1916, p. 57.

choosing to draw it at the top, where the change from sandstone to limestone forming conditions is fairly abrupt, rather than at the more or less transitional calcareous to arenaceous boundary at the base of the Mahto.

CONTACT BETWEEN THE LOWER CAMBRIAN AND PRE-CAMBRIAN (§ 9)

The contact of the Lower Cambrian sandstones with the pre-Cambrian rocks in the Robson district is described by Walcott (pages 329-330) as finely shown "to the north, west, south, and southwest of Yellowhead Pass, in Mount McEvoy (Mount Toot Toot), and Yellowhead Mountain, Mount Fitzwilliam (Mount Pelée), and other high points from 8 to 20 miles east to the mouth of the Moose River." The contact was not studied by the writer, and since difficulties were encountered by Walcott in drawing the boundary, we lack definite knowledge of the relations between the two series.

TOPOGRAPHIC FEATURES, WITH DETAILS AS TO SYNONYMY AND STRATIGRAPHY

CHETANG CLIFF (§ 10)

Chetang Cliff is a new name applied by Walcott to a cliff southwest of Coleman Brook. The cliffs expose the Chetang limestones, but the contact with the underlying formations and the portion up to and including the *Albertella* fauna is much better exposed in the summit of Mumm Peak.

THE EXTINGUISHER (§ 11)

The Extinguisher,¹⁷ a small cone of black rock in the Robson glacial cirque, is referred to by Walcott as Billings Butte. Its especial interest lies in the fact that the fauna found in its rocks is, so far as we know, the youngest in the Mount Robson region, and outcrops in place in the beds immediately overlying those forming the summit of Mount Rear-guard (§§ 23*c* and 23*f*). It is not improbable that the fauna occurs near the summit of Mount Robson itself (§§ 23*d-e*). The Extinguisher beds are much higher stratigraphically than those in the top of Lynx Mountain (§ 24*d*).

MOUNT HITKA (§ 12)

Mount Hitka is a name given by Walcott to the high ridge northeast of Mumm Peak and separating that peak from the valley of the Smoky River. From it is derived the name of a formation which he describes as occurring between the Tatay beneath and the "Mumm" above. As we

¹⁷ Coleman: The Canadian Rockies, new and old trails.

have shown (§ 27*b*), there is duplication, and the beds called "Hitka" are those called Titkana in the mountain of the latter name.

HOTA CLIFF (§ 13)

Hota cliff, on the northeast side of Coleman Brook, is in a position to expose the Hota formation if there is no faulting to the southwest; but the exposures are very poor, the contacts with the overlying Chetang and the underlying Mahto are covered, and no fossils are recorded by Walcott. The description of the rocks bears no resemblance to that of the rocks occupying the corresponding stratigraphic position in Mumm Peak, where the contacts and every foot of the formation are exposed (§ 30*g*).

LYNX MOUNTAIN (§ 14)

Lynx Mountain: Wheeler, 1912, *Canadian Alpine Journal*, volume 4, map.
Phillips Mountain: Walcott, 1913, *Smithsonian Miscellaneous Collections*, volume 57, number 12, page 333, plate 57, figure 2, and plate 58, figure 1.
(Credited by Walcott with a height of 9,542 feet, which is the height of Lynx Center Station of Wheeler.)

Lynx Mountain (10,471 feet high) is the topographic feature to which Walcott has applied the name "Phillips" (§ 17), his photographs leaving no doubt as to the mountain meant. The mountain to which he applies the name Lynx is a still unnamed peak, of unknown height, southwest of Lynx Mountain.

Walcott's description of the Lynx formation states that it forms almost the entire mountain to which he gave that name, but we are not certain of its presence in this snow-and-ice-covered peak. The Lynx formation does outcrop, however, in Walcott's "Phillips Mountain"; and, since this is the real Mount Lynx, the name Lynx is entirely appropriate to the formation (§ 24).

MAHTO MOUNTAIN (§ 15)

Mahto Mountain was proposed by Walcott for the ridge separating Smoky River from Calumet Creek. The Mahto formation is better exposed, because of its observable relations to fossiliferous overlying and underlying formations in Mumm Peak (§ 16), but the name Mahto has been retained.

MUMM PEAK (§ 16)

Mumm Peak¹⁸ (9,740 feet) is the high point directly north of Mount Robson, on the north side of Robson Pass, and is described by Walcott as exposing the Hota, the Mumm (typically), and the Titkana, and by

¹⁸ Wheeler: *Canadian Alpine Journ.*, vol. 4, 1912, p. 36.

necessity the intervening Chetang, Tatei, and Hitka formations. As a matter of fact, the so-called "Hota," just above the Mural Glacier,¹⁹ is the "Tah" (§§ 30*d*, 32*b-e*), and the top of the mountain does not expose the Titkana, but the Chetung (§§ 26*b* and 29*b*). The succession in Mumm Peak is not (reading from the base upward) "Hota," Chetang, Tatei, Hitka, Mumm, and Titkana, but "Tah," Mahto, "Hota," and Chetang (§§ 30*g* and 32*c*).

"PHILLIPS MOUNTAIN" (§ 17)

Phillips Mountain was proposed by Walcott (page 333) for a station (Lynx Center, 9,542 feet) which Wheeler²⁰ was forced, by the lateness of the day, to occupy on the crest of the north arête of Lynx Mountain, but in his illustrations (plates 57 and 58) Walcott applies the term Phillips to Lynx Mountain, assigning to the latter an elevation of only 9,542 feet and crediting the unnamed peak between Mounts Resplendent and Lynx with the name Lynx and the height (10,471 feet) determined by Wheeler for the real Mount Lynx. Lynx Center Station lies on the sky line of Walcott's figure 2 of plate 57, half way between the two glaciers to the left of the summit (see the plate opposite page 22 of Wheeler's report, which represents the view from this point).

MOUNT REARGUARD (§ 18)

Mount Rearguard (9,000 feet) was named by Coleman²¹ and confirmed by Wheeler.²² It is the mountain which Walcott suggested changing to Iyatunga; but the new name has not appeared in the decisions of the Geographic Board of Canada. The mountain is described by Walcott as one of the two mountains best exposing the Middle Cambrian Titkana limestones; but examination of the section showed that even the oldest rocks exposed in the mountain lie much higher than the Middle Cambrian Titkana. The mountain affords a wonderful and very fossiliferous section of the Upper Cambrian from the Extinguisher Ordovician fauna, at the top, to low down in the Lynx formation, at the base.

MOUNT ROBSON (§ 19)

Mount Robson (13,068 feet) is already so well known that we shall not discuss its discovery or nomenclature. A brief discussion of the wonderful section exposed will be found under the heading "Robson

¹⁹ Smithsonian Misc. Coll., vol. 57, no. 12, 1913, pl. 59, fig. 1.

²⁰ Canadian Alpine Journ., vol. 4, 1912, p. 19.

²¹ The Canadian Rockies, new and old trails.

²² Canadian Alpine Journ., vol. 4, 1912, p. 36.

limestones" (§ 23). With the rocks as abundantly fossiliferous as they are, it is to be hoped that some mountain-climber who reaches the top will slip a small chunk of the rock in his pocket before beginning the descent.

TAH MOUNTAIN (§ 20)

Tah Mountain was proposed by Walcott for the peak occupied by Wheeler as Moose Pass Station (see his map of 1912). Walcott uses the name for the "Tah" formation, but Tah Mountain has not received the approval of the Geographic Board, and the published description of the formation has been so confused (§§ 30*a-d*, 32*b-e*) that we have given to it the name of Mural limestone formation (§ 32*g*).

TATEI CLIFFS (§ 21)

Tatei cliffs (revised by the Geographic Board of Canada from "Tatay" of Walcott) is a name applied to the uppermost of three cliffs southwest of Coleman Brook and above and to the southwest of Chetang cliff for the purpose of obtaining a formation name which has been retained.

TITKANA PEAK (§ 22)

Titkana peak (9,320 feet) was first called Ptarmigan Peak by Coleman, who thus duplicated the name of a mountain north of Lake Louise, on the Canadian Pacific Railway. The name Ptarmigan was also given to the pass between the mountain of that name and Lynx Mountain. Wheeler²³ calls attention to the duplication and suggests Snowbird Mountain and Pass, but on his map he applies the term Snowbird to the pass only. Walcott accepts Snowbird for the pass, but proposes a new name, Titkana, for the peak, and the latter has been accepted by the Geographic Board of Canada.

The section exposed in the mountain corresponds with Walcott's general description, so far as the Titkana limestones are concerned, the only changes made in the present paper being in the total thickness and in the discovery of many abundantly fossiliferous horizons. The underlying limestones in the cliffs above Lake Adolphus, which Walcott refers to the "Mumm," are, however, to be referred to the Tatei instead (§§ 26 and 28).

²³ Canadian Alpine Journ., vol. 4, 1912, p. 37.

GEOLOGIC FORMATIONS, WITH DETAILS AS TO SYNONYMY AND STRATIGRAPHY

"ROBSON LIMESTONES" (§ 23)

(§ 23*a*.) The "Robson limestones" are estimated by Walcott to extend from the summit of Mount Robson some 3,000 feet down, and are described as "light gray or dove-colored and bluish gray, thin-bedded limestones," the upper half, or 1,500 feet, being described as practically inaccessible in the summit of the peak and appearing to be more massive bedded and arenaceous than the beds below.

(§ 23*b*.) Two fossil localities are described, one in drift blocks brought down by the "Chupo Glacier" (61*u*), which is stated to "indicate a horizon very close to, if not within, the base of the Ordovician," and the other (61*q*) in the Extinguisher ("Billings Butte").

The species listed by Walcott from the drift on the "Chupo Glacier" certainly form an assemblage which the average paleontologist would have little hesitancy in placing in the Cambrian, with the possibilities as much in favor of the Middle as the Upper. However, one opinion regarding the actual fossils is worth more than a number of opinions based on a list of species. We can only call attention to the fact that it is a drift locality, to the fact that there are thousands of feet of Middle and Upper Cambrian beds outcropping above the place in which it was found, and to the fact that it appears to be represented in the collections at our disposal from the Mount Robson region in the limestones of the Titkana formation.

(§ 23*c*.) The species listed by Walcott from locality 61*q* in the Extinguisher are described as an assemblage "of Upper Cambrian and Ordovician types," which indicate the base of the Ordovician. For this reason the isolated²⁴ Extinguisher beds are referred by Walcott to the lower portion of the "Ordovician Robson limestones." The discovery of the Extinguisher beds and fauna in the uppermost portion of the Mount Rearguard section has, however, afforded us data as to the actual relations existing between the Extinguisher beds and the Lynx limestones, and consequently between the Ordovician and the Upper Cambrian.

(§ 23*d*.) The writer secured known fossil horizons in the limestones of Mount Robson 1,600 feet above the level of Berg Lake, or at an elevation above sealevel of about 7,100 feet. Since Mount Robson has an alti-

²⁴ Walcott (Ann. Rept. Smithsonian Inst. for 1915, p. 252, and Nat. Geog. Mag., vol. 24, 1913, p. 633, legend) speaks of a "satisfactory tie" made on the basis of dips, but a visit to Mount Rearguard, which must have shared in such a visual correlation, shows it not to be "Middle Cambrian," but Upper Cambrian in age, and leaves the position of the Extinguisher fauna in Mount Robson open (§§ 23*f*, 24*d*).

tude of 13,068 feet, there is room for some 6,000 feet of beds (the strata are very nearly horizontal) between the fossil horizon secured and the top of the mountain. Now, the fossil horizon secured is equivalent to the base of bed number 11 in the Titkana limestones, 1,100 feet below the top of the formation, which, with the thickness of the Lynx limestones (4,950 feet); yields a total thickness of 6,050 feet between the 7,100-foot (elevation) fossil horizon and the Extinguisher fauna. The stratigraphic position of this fauna (Extinguisher) and the top of the mountain should, therefore, coincide, and from this point of view there seems to be no room in the top of Mount Robson for strata younger than those carrying the Extinguisher fauna.

(§ 23e.) The unbroken section of 9,809 feet, stretching from the summit of Mount Robson (13,068 feet) down to the level of Lake Kinney (3,259 feet), which lies close to the top of the basal clastics, also yields a figure which compares very favorably with the 9,850 feet of measured beds between the basal clastics and the Extinguisher fauna. Of course, 50 feet in 10,000 is more accurate than the rocks are, to say nothing of the measuring, and we do not know the extent of the break in the Lynx Mountain section or just how far below the surface of Lake Kinney the basal clastics begin; but while the closeness of the correspondence is purely adventitious, the approximation confirms our interpretation of the stratigraphy.

(§ 23f.) Above the Lynx limestones there is a thin-bedded series of shales and interformational conglomerates (375 feet exposed) carrying an abundance of Ordovician fossils (the Extinguisher fauna); and while these have nothing in common with the published descriptions of the "Robson limestones," except possible occurrence on the top of Mount Robson, they might, perhaps, receive the name Robson shales at the hands of a future student who shall find them there. They do occur in the Extinguisher and in the summit of Mount Rearguard.

LYNX FORMATION (§ 24)

(§ 24a.) The Lynx limestones are described by Walcott as unfossiliferous and as beginning on the south slope of Titkana Peak, near Snowbird Pass, and extending over "Phillips Mountain" (Lynx Mountain) into the base of "Billings Butte" (the Extinguisher), to the horizon of the Extinguisher fauna, with a thickness of 2,100 feet.

(§ 24b.) As determined by sections measured back of the summit of Titkana Peak, in Lynx Mountain (Walcott's "Phillips"), and in Mount Rearguard (Walcott's "Iyatunga") (§§ 17 and 18), the Lynx formation has a thickness of 4,950 feet to the horizon of the Extinguisher fauna, is

abundantly fossiliferous, and is one of the most heterogeneous of the formations in the region.

(§ 24*c*.) The Lynx formation extends from the base of the Upper Cambrian to the base of the Ordovician. It is marked at the base by a series of shales which exhibit shallow-water phenomena (§ 1), and, like the Upper Cambrian in so much of the Cordillera, is frequently characterized by interformational conglomerates. The limestones forming the upper part of the Lynx formation are cliff-forming, and the line between the Upper Cambrian and the Ordovician is drawn between them and an overlying series of shales and thin interbedded interformational conglomerates which carries the Extinguisher fauna and which is referred to the Ordovician. The line occurs about halfway up in the section exposed in the Extinguisher and at the top of Mount Rearguard.

(§ 24*d*.) Walcott describes the Lynx formation as lying below the Extinguisher fauna—a definition which is accepted—one of the reasons for the discrepancy between the figures of 2,100 and 5,000 feet respectively for the thickness of the formation being his assumption that Mount Rearguard exposed the Middle Cambrian, and that the Extinguisher beds directly overlay those of Mount Lynx. Mount Rearguard exposes the upper portion of the Lynx and is itself directly overlain by the Extinguisher beds and fauna. Mount Lynx exposes only the lower portion of the Lynx formation.

Titkana limestones: Walcott, Smithsonian Miscellaneous Collections, volume 57, number 12, 1913, pages 330, 334, 337, and 341.

Hitka formation, as far as both position in section and exposure in Hitka Mountain: Walcott, *idem*, pages 334, 338, and 341.

Titkana: Burling, Museum Bulletin number 2, Geological Survey of Canada, 1914, page 109.

Hitka: Burling, *idem*, page 109.

Titkana: Walcott, Problems of American geology, New Haven, 1915, page 179.

Hitka: Walcott, *idem*, page 179.

TITKANA LIMESTONES (§ 25)

(§ 25*a*.) According to Walcott, the Titkana limestones have an estimated thickness of 2,200 feet and are best seen in the west slopes of Titkana Peak and in Mount Rearguard ("Iyatunga"). As has already been shown (§§ 18 and 24*d*), this formation is not present at all in Mount Rearguard, but the section in Titkana Peak exposes both the top and bottom of the formation.

Two fossil horizons were secured by Walcott—one, locality 61*v*, in a cliff just above the Robson Glacier, and the other (61*l* and 61*m*) 1½ miles west-northwest of the summit of Titkana Peak. The first of these

localities (61*v*) contains a fauna comparable to the fauna of the Stephen formation in the Canadian Pacific Railway section, and is represented in our collections from the mountain (Titkana) itself by a locality 600 feet above the base of the formation. The second of the two localities (61*l* and 61*m*) is represented in our collections from both Titkana Peak and "Mount Hitka" by a locality at the base of the formation 600 feet below the horizon of the Stephen fauna.

(§ 25*b*.) As has been described under the "Hitka" (§§ 12 and 27*b*), there appears to be duplication involving that formation and the Titkana. Our reason for choosing the term Titkana and abandoning the Hitka is that while the former is stated to be unfossiliferous, Walcott found two fossil horizons in the Titkana, and the latter formation is much better exposed in the peak of the same name than is the Hitka in Mount Hitka. A comparison of the abundant fossils found in many horizons of the "Hitka" and the Titkana confirms their identity.

"MUMM LIMESTONES" (§ 26)

(§ 26*a*.) According to Walcott, the "Mumm limestones" are Middle Cambrian, massive-bedded, gray, arenaceous limestones weathering to gray and buff tints, with an estimated thickness of 600 feet, and occur (1) in the northwest base of Titkana Peak (= Tatei limestones), (2) on the westward slope of the ridge east-northeast of the lower end of Lake Adolphus (= Tatei limestones), and (3) in the upper part of Mumm Peak (= Hota limestone). No fossils were found.

(§ 26*b*.) As has been stated already (§ 16), inspection of the rocks forming the top of the mountain proved them to belong to the Chetang, a formation which is described by Walcott as lying 2,500 feet below the "Mumm," and is, according to his section, separated from that formation by two other formations. The Mumm limestones are, therefore, non-existent, so far as Mumm Peak is concerned—in fact, the limestone to which the name was there applied is the "Hota" (§§ 30*b*, 30*g*, and 32*c*). We have shown (§§ 28 and 27*b*) that the limestones in localities 1 and 2 above are to be referred to the Tatei, and that there is a duplication in Walcott's section which involved the confusion of the Mumm with the Tatei and the Hitka with the Titkana. The absence of any fossils in Walcott's collections from the Mumm, Hitka, and Tatay formations, 3,100 feet, made the identification of his section in the field a slow process, the problem being further complicated by the facts (*a*) that neither the Mumm limestone nor any limestone of the age assigned to the Mumm occurs in the mountain in which it is stated to be typically developed (§ 32*c*), and (*b*) that the "Hitka," in the mountain of that

name, is not overlain by the massive limestones of the Mumm, but by a series of red shales indistinguishable from the basal Lynx (§ 27b). For these reasons we have not used the name Mumm in this paper.

"HITKA FORMATION" (§ 27)

(§ 27a.) The "Hitka formation" is described by Walcott as occurring (a) between the Tatay cliffs and the Mumm limestones, on the westward slope of the ridge east-northeast of the lower end of Lake Adolphus, and (b) in Hitka Mountain.

(§ 27b.) Five formations were found by the writer in Mount Hitka—a middle one underlain by two limestones referable to the Tatei and the Chetang respectively (all fossiliferous) and overlain by red and yellow shales referable to the Lynx. If the "Hitka" is the upper red and yellow shales, it is underlain by the Titkana instead of the Tatei; if it is the middle formation, it is clearly identical with the Titkana. The fossils amply corroborate this.

TATEI LIMESTONES (§ 28)

Mumm limestones (locality near lower end of Lake Adolphus): Walcott. Smithsonian Miscellaneous Collections, volume 57, number 12, 1913, page 330.

Not Mumm limestones, given as typically exposed in upper part of Mumm Peak: Walcott, *idem*, pages 334, 337 (= Adolphus, §§ 30a, 30b, 30g, and 32c).

Mumm limestones, so far as position below Titkana limestones in general section is concerned: Walcott, *idem*, pages 334, 337, 341.

Mumm limestones, exposure at northwest base of Titkana Peak: Walcott, *idem*, page 337.

Not Mumm limestones, so far as description is concerned: Walcott, *idem*, pages 334, 337, 341 (drawn from an outcrop of the "Hota").

Tatay limestones, so far as position above the Chetang and occurrence in Tatei cliffs is concerned: Walcott, *idem*, pages 334, 338, and 341.

Mumm formation: Burling, Museum Bulletin number 2. Geological Survey of Canada, 1914, page 109.

Tatay formation: Burling, *idem*, page 109.

Mumm formation: Walcott, Problems of American geology, 1915, page 179.

Tatay formation: Walcott, *idem*, page 179.

(§ 28a.) The Tatei limestones are described by Walcott as being massive-bedded, gray, siliceous, and arenaceous, with an estimated thickness of 800 feet and without fossils.

(§ 28b.) As has been described in the discussion of the "Hitka limestones" (§ 27) and the "Mumm limestones" (§ 26), this formation overlies the Chetang and underlies the Titkana instead of the "Hitka," both

the "Hitka" and the "Mumm" representing duplications in the section and being none other than the Titkana and the Tatei respectively.

CHETANG LIMESTONES (§ 29)

(§ 29*a*.) According to Walcott, these are Middle Cambrian in age, have an estimated thickness of 900 feet, and outcrop in Chetang cliff. Fossils were found by Walcott in the Chetang limestones and the formation affords a known point from which to begin our interpretation of Walcott's section of the over- and under-lying rocks.

(§ 29*b*.) Though the formation can be seen and is fossiliferous at the type locality, exposures are there poor, especially with regard to the upper and lower boundaries, and the latter is important, since it is described by Walcott as involving the contact between the Lower and the Middle Cambrian. This conception of the stratigraphy differs from the one presented in this paper (§§ 8, 30*e*). The lower part of the Chetang limestones is very well exposed and is very fossiliferous at the top of Mumm Peak (§§ 16, 26*b*, 30*g*, 32*c*), but erosion has there removed the overlying rocks. Several *Albertella* horizons were also found in a section exposed in the gorge below Mural Glacier.

ADOLPHUS ("HOTA") LIMESTONE (§ 30)

Hota formation, so far as position in the section is concerned: Walcott, Smithsonian Miscellaneous Collections, volume 57, number 12, 1913, pages 335, 338, and 341. (The description of lithology and the lists of included fossils are derived from an exposure of the "Tah" (Mural limestone) in Mumm Peak, just above the Mural Glacier, which was mistaken for the Hota) (§§ 30*d*, 32*b*).

Mumm limestones, so far as both description and position in Mumm Peak are concerned: Walcott, *idem*, pages 334, 337 (§§ 30*g*, 32*c*).

Not the Mumm limestones listed as occurring near lower end of Lake Adolphus: Walcott, *idem*, page 330 (= Tatei, §§ 22 and 26*b*).

Not the Mumm limestones listed as occurring in northwest base of Titkana Peak: Walcott, *idem*, page 337 (= Tatei, §§ 22 and 26*b*).

Hota formation, so far as position in the section is concerned: Burling, Museum Bulletin number 2, Geological Survey of Canada, 1914, page 109.

Hota formation, so far as position in the section is concerned: Walcott, Problems of American geology, 1915, page 179.

(§ 30*a*.) The "Hota formation" is described by Walcott as composed of a series of "gray arenaceous limestones and siliceous shales alternating with massive quartzitic sandstones," 800 feet thick and lying beneath the limestones of the Chetang formation on the southwest side of Coleman Brook. By definition it is the formation separating the Mahto from the Chetang.

(§ 30*b*.) Now, the formation occupying this position in the continuous and fossiliferous section of the "Tah," Mahto, "Hota," and Chetang formations (§§ 16 and 32*c*) exposed in Mumm Peak is a massive 300-foot cliff-forming, gray arenaceous limestone, with transitional clastics at the base; and it is this bed which Walcott took to be a younger limestone, 3,400 feet higher in the section than the "Hota," and to which he gave the name "Mumm limestone" (§§ 26*b* and 32*c*).

(§ 30*c*.) Walcott (page 339) refers to the "Hota" as the "New Lower Cambrian subfauna" described by him in the preceding number of the *Miscellaneous Collections* (volume 57, number 11). This fauna was mostly collected from drift blocks on the surface of Mural Glacier, but Walcott (legend to plate 59) locates the horizon in the cliffs just above the glacier.

(§ 30*d*.) A section of the beds in this locality, beginning at the glacier, passes up through the "Tah" into the Mahto sandstones, and shows (*a*) that the beds in the position indicated by Walcott lie approximately 2,500 feet below the "Hota," and (*b*) that the general description given for the lithology of the "Hota" was derived from an exposure of the "Tah"; for, unless Walcott's "Hota" is incorrectly defined as underlying the Chetang and really lies 2,500 feet below that formation and beneath a massive series of quartzites, the beds containing the "New Lower Cambrian subfauna" can in no way be referred to the "Hota" and must be referred to the "Tah" (see § 32).

(§ 30*e*.) Walcott places the "Hota" formation in the Lower Cambrian, but the *Olenellus*, on which this correlation is based, occurs in the "Tah" at a place where the latter had been identified as "Hota." Naturally, therefore, the line between the Lower and Middle Cambrian was drawn at the top of the "Hota"; but we have found typical Middle Cambrian fossils in the base of the "Hota" without *Olenellus*, and have drawn the Lower-Middle Cambrian boundary below (§§ 8, 30*f*, 31*c*, 32*d*, 32*e*).

(§ 30*f*.) It will be noticed that our generalized sections (§ 2) gives the "Hota" (Adolphus) a thickness 400 feet less than Walcott, and it should be stated that neither the addition of 400 feet from the overlying Chetang, nor the addition of any number of feet up to one thousand, apparently, from the underlying Mahto would add Lower Cambrian fossils to the "Hota," though it would explain the reference to quartzites in Walcott's description of the "Hota."

(§ 30*g*.) Lest any one should think that the differences between Walcott's interpretation and my own are due to failure correctly to identify his formations, it may be stated that his "Hota" is the formation underlying the Chetang, however it is described lithologically, and the Chetang

is one of the three formations in which Walcott found fossils. Its identification at the type locality as well as in Mumm Peak is based on indisputable fossil evidence, and the formation directly underlying it in Mumm Peak must, therefore, be the "Hota." That this is so is further proved by the presence, below the Mumm Peak "Hota," of a series of quartzitic sandstones comparable with the Mahto; and this section (Chetang, "Hota," and Mahto), reading from the top down, overlies, in one unbroken, perfectly exposed section (§§ 16 and 32*c*), the beds in which Walcott secured the "New Lower Cambrian subfauna" and which he thought to be the "Hota" of Hota cliff.

For the sake of clearness, I have used the term "Hota" in speaking of this limestone in the preceding pages, but we have in this paper discarded the term "Hota" and adopted the name Adolphus, for the following reasons:

(*a*) Without fossils or observable upper and lower contacts, we can not be at all sure that the "Hota" even outcrops in the ridge named, but it does outcrop in the cliffs of Mumm Peak above Lake Adolphus in observable relations to the overlying Chetang and the underlying Mahto (§§ 16 and 32*c*).

(*b*) The published descriptions of the "Hota" are based on exposures of the "Tah" (§ 30*d*).

(*c*) The real "Hota" (the limestone immediately underlying the indisputable Chetang, which forms the summit of Mumm Peak) is described, located, and given the name Mumm (§§ 26 and 32*c*).

(*d*) The fossils credited to the "Hota," and these include a very important assemblage of Lower Cambrian fossils, did not come from the "Hota," but from the "Tah" (§§ 30*c*, 30*d*, 32*c-e*).

(*e*) The "Hota" is described as Lower Cambrian, but it is so referred on the basis of fossils occurring a thousand or more feet lower in the section (§ 8*a*) and of a "New Lower Cambrian subfauna" which occurs 2,500 feet below (§ 30*d*). The "Hota" (Adolphus) is Middle Cambrian in age.

MAHTO SANDSTONES (§ 31)

(§ 31*a*.) The Mahto sandstones are described by Walcott as occurring between the more or less calcareous "Tah" (= Mural) limestone formation beneath and the similar, though more limy, "Hota" (= Adolphus) above. It was credited at first with the "new Lower Cambrian subfauna" which he later took out of the Mahto and assigned to the overlying "Hota" (§§ 30*c*, *d*, *e*, 32*d*, *e*).

(§ 31*b*.) The Mahto is described by Walcott as unfossiliferous and the boundaries we have drawn (§§ 30*e*, *f*, *g*, 32*e*) leave it without fossils as

well. The very base of the overlying "Hota" contains typical Middle Cambrian fossils, and the underlying "Tah" is abundantly fossiliferous, all of the horizons discovered in the latter being Lower Cambrian.

(§ 31c.) The Mahto sandstones therefore represent an apparently unfossiliferous quartzitic series between the Middle Cambrian and the first *Olenellus*,²⁵ and the line between the Lower and the Middle Cambrian is drawn at the top of the Mahto formation (§§ 8, 30e, 30f).

(§ 31d.) Our estimated thickness of 1,200 feet for the Mahto in Mumm Peak differs from Walcott's estimate of 1,800 feet for its thickness in Mount Mahto, five miles away. The relation of the arenaceous beds above to the calcareous beds below, which is the basis on which the line is drawn in Mumm Peak, may vary in the distance separating the latter peak from Mount Mahto.

MURAL ("TAH") LIMESTONE FORMATION (§ 32)

Mahto formation, as the name for the beds carrying the "new Lower Cambrian subfauna": Walcott, Smithsonian Miscellaneous Collections, volume 57, number 11, 1913, pages 311-316. (According to Walcott, § 32d, this use of the term Mahto was by error.)

Hota formation, as the name for the beds carrying this fauna: Walcott, idem, number 12, 1913, page 339. (An error in identification, § 32c.)

Tah formation, as the unfossiliferous formation between the Mahto and the McNaughton: Walcott, idem, pages 335 and 339.

Tah formation: Burling, Museum Bulletin number 2, Geological Survey of Canada, 1914, page 109. (On page 108 the reference of the "new Lower Cambrian subfauna" to the Hota is questioned.)

Tah formation: Walcott, Problems of American geology, 1915, page 179.

Mahto formation: Walcott, Annual Report of the Smithsonian Institution for 1915, plate 17, 1916, page 254. (A reversion by inadvertence to the nomenclature of the first reference, § 32d.)

Mahto formation, as the formation carrying one of the new Lower Cambrian subfauna forms (*Padeumias*): Burling, Bulletin of the Geological Society of America, volume 27, 1916, pages 158-159. (The error of placing this fauna in the overlying "Hota" had been recognized, but the line between the Mahto and the underlying "Tah" was at this time drawn so as to include the fauna in the Mahto—§§ 31b, 32d, 32e.)

Mahto formation, as the formation carrying the *Padeumias* above mentioned: Burling, Ottawa Naturalist, volume 30, 1916, page 55. (See note to preceding reference.)

(§ 32a.) The "Tah" formation is described by Walcott as occurring just above Moose Pass, at the base of "Tah Mountain," with a thickness

²⁵ It is, of course, possible that the *Olenellus* fragments credited to the Mahto on page 335 of Walcott's paper did come from the Mahto, and that the formation is not unfossiliferous, as stated on page 369, and the rocks are so frequently fossiliferous that many may be found in the Mahto by the next observer.

of 800 feet, unfossiliferous, and resting on a few layers of McNaughton sandstones before the whole section is cut off by a fault which brings down the Upper Cambrian.

(§ 32*b*.) This formation is the one which Walcott found occurring just above the "new Lower Cambrian subfauna" in the moraine of the Mural Glacier and identified as "Hota" (§§ 30 and 31). This threw out the whole Mumm Peak section and resulted in the identification of the thin-bedded quartzites of the Mahto as the Chetang and the description of the real "Hota" (now called Adolphus), which stands out clear and distinct as a cliff above, for a new and much higher limestone, to which the name Mumm was given.

(§ 32*c*.) It should be recorded that when I reached the summit of Mount Hitka, approaching it from the valley of Smoky River, I did not know that the faulting between Mount Hitka and Mumm Peak was as large as it is, and I had not the slightest doubt that I was viewing the section described by Walcott—Mumm, Hitka, Tatei, Chetang, and Hota, listing them from the top down. I was the most surprised of individuals when I started up the north face of Mumm Peak, and, after passing through Walcott's "Hota," with its profusion of *Olenellus* (the "new Lower Cambrian subfauna"), reached a quartzitic series more than a thousand feet in thickness, instead of the Middle Cambrian Chetang limestones. It was not until I reached the summit of Mumm Peak from the south side that I could realize (*a*) that the limestone to which Walcott had applied the name "Mumm" was really the "Hota," and (*b*) that the Mural Glacier fossils (the "new Lower Cambrian subfauna") came not from the "Hota," but from a horizon approximately 1,750 feet below.

(§ 32*d*.) I first drew the line between the "Tah" and the Mahto below bed number 8 of the north face section, and in my description of *Pædeumias robsonensis*²⁶ I referred this form to the Mahto. This coincided with Walcott's reference of the "new Lower Cambrian subfauna," of which *Pædeumias robsonensis* is a member, to the Mahto.²⁷ I thus ignored the fact that the same fauna had been referred three days later²⁸ to the "Hota," and accepted its re-reference to the Mahto three years later.²⁹

This reference of *Pædeumias robsonensis*, and therefore of the new subfauna, to the Mahto was, however, questioned by Mr. Resser, of the United States National Museum, in a personal communication:

²⁶ Ottawa Nat., vol. 30, 1916, p. 55.

²⁷ Smithsonian Misc. Coll., vol. 57, no. 11, 1913 (July 21), pp. 309-326.

²⁸ Idem, no. 12, 1913 (July 24), pp. 338, 339.

²⁹ Ann. Rept. Smithsonian Inst. for 1915, pl. 17, p. 254, 1916.

"In the description of the species *Pædeumias robsonensis* you give the horizon as Mahto. Walcott in his description of this fauna gives it thus also, but in his next paper (July 24) he gives the fauna as occurring in the Hota. I called his attention to this difference and he says the correct formation is the Hota."

(§ 32*e*.) As we have shown (§§ 30*c*, *d*, *g*, and 32*c*), the "new Lower Cambrian subfauna" of Walcott occurs not in the "Hota," but in the Mahto or the "Tah." In the absence of any recognizable break, the line between these two formations has now been drawn (§ 8*b*) so as to include in the overlying Mahto only the dominantly arenaceous series and so as to transfer to the underlying "Tah" the essentially calcareous series. Such a separation places the "new Lower Cambrian subfauna" 550 feet below the top of the "Tah" (Mural limestone) formation.

The differences between the interpretations of Mr. Walcott and myself are in no way dependent on the drawing of the line between the "Tah" and the Mahto. He said, and repeats through Mr. Resser, that the "new Lower Cambrian subfauna" came from the "Hota," a formation *overlying* the Mahto. We have visited the type locality and have found the fauna under discussion in the "Tah," a formation *underlying* the Mahto.

(§ 32*f*.) The Mural limestone formation is one of exceptional interest; and while all of the fossils secured by Walcott, as well as the specimens described by the writer, were secured from drift blocks in the lateral moraine of the Mural Glacier, an abundant fauna has now been secured from the formation itself. In addition to being very fossiliferous in its locality above the Mural Glacier on Mumm Peak, the Mural limestone formation is there shown in observable relations with its over- and underlying formations. The underlying sandstones (not certainly to be correlated with the McNaughton sandstones of Walcott) are here over 400 feet thick.

(§ 32*g*.) Our main reasons for making the change from "Tah" to Mural are the failure of the Geographic Board to accept the name, the remoteness of the mountain, the absence there of observable relations to the other formations and of fossils, and the confusion of the "Tah" and the "Hota," stratigraphically, lithologically, and paleontologically.

MC NAUGHTON SANDSTONES (§ 33)

(§ 33*a*.) The McNaughton sandstones are described by Walcott from the McNaughton Mountains, some 20 miles distant from the locality in which the other formations were identified. They are there given an estimated thickness of 500 feet and are described as unfossiliferous. The

drawing of a line between them and the Miette sandstones is described as a matter of some difficulty (§ 9).

(§ 33*b*.) The quartzitic limestones which underlie the Mural limestone formation in the Mount Robson region may or may not be directly underlain by the pre-Cambrian, and may or may not be correlateable with the McNaughton sandstones. Even though they form, so far as known, the exposed base of the Cambrian sequence in the Mount Robson region, we prefer to leave their naming to the future student who shall determine their relations to the pre-Cambrian.

MIETTE SANDSTONES (§ 34)

The Miette sandstones are described by Walcott as having an estimated thickness of 2,000 feet, and as being best exposed along both sides of Yellowhead Pass from Grant Brook on the west to Fitzhugh on the east, and to be overlain by the McNaughton sandstones, the line of demarcation being very uncertain. The writer did not find the contact between the Cambrian and the pre-Cambrian in the Mount Robson region and is unable to add to the description given (§ 9).

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